Minnesota Department of Transportation

Full-Depth Reclamation (FDR) for Suburban/Urban and Local Roads Application

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Full-depth reclamation (FDR) as a rehabilitation method improves the service life of pavement structures by reusing asphalt materials, thereby reducing costs and allowing for conservation of nonrenewable resources. However, the lack of mechanics-based material testing procedures and performance-based specifications limit the use of FDR processes. First, the FDR design and construction process are presented, then, a literature review focusing on FDR research is completed, and a survey is conducted to obtain relevant information regarding current FDR practices in Minnesota. Next, Indirect Tensile Test (IDT) and Dynamic Modulus Test in IDT mode testing is performed on four FDR materials: Field mixed, Lab compacted; Lab mixed, Lab compacted; FDR with cement additive; and FDR with graphene nanoplatelet (GNP) additive. Two curing times are used to determine how physical properties change over time. Test results are used to perform simulations in MnPAVE software and a Life Cycle Cost Analysis (LCCA). Laboratory observations indicate that cement additive reduces predicted life and increases critical cracking temperature with a slight increase in cost; GNP additive reduces predicted life but also reduces critical cracking temperature with a significant cost increase; Lab mixed samples performed better than Field mixed, suggesting that field methods could be improved; and curing has a positive effect on the FDR materials with cement and GNP additives--for both materials, the dynamic modulus increase, and the GNP samples also had a slight increase in tensile strength. MnPAVE simulations and LCCA results indicate that over a 35-year period, FDR may be a more cost-effective method than traditional mill and overlay.

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FULL-DEPTH RECLAMATION (FDR) FOR SUBURBAN/URBAN AND LOCAL ROADS APPLICATION

FINAL REPORT

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CHAPTER 1: INTRODUCTION

The use of cold-recycled materials in the rehabilitation of asphalt pavements, and in particular the use of full-depth-reclamation (FDR), has gained a lot of attention and has seen a steady increase in use since it allows for improving the service life of pavement structures at reasonable costs through a relatively simple construction process, conservation of nonrenewable resources, and improvements of existing road grades. In general, the FDR design and construction process includes the following stages:

1. *Preliminary analysis*. The candidate pavement is evaluated to determine the condition of the road and assess the types and levels of distress present. For urban conditions, particular attention is given to utilities conflicts and matching of existing curbs and gutters.
2. *Existing pavement testing*. The existing pavement structure is tested to determine relevant properties. Cores and base material are removed every 500 ft. Laboratory tests such as resilient modulus, maximum dry density, plasticity index, sand-equivalence, gradation, and optimum moisture content are performed. Falling weight deflectometer is used to determine the granular equivalency GE or structural number of the candidate road in the same locations where cores are taken.
3. *FDR design*. Based on the preliminary testing results, a design is selected as follows:
   a. A suitable additive (if necessary) is selected and a mix design is performed in laboratory conditions. Laboratory prepared specimens are tested to obtain relevant properties such as indirect tensile strength, resilient modulus or dynamic modulus. The results are sometimes used to refine the mix design.
   b. The reclamation method is selected. The most common practice is to use a reclaiming machine. An alternative, but more expensive method is to use a mobile cold recycling mixing plant, located close to the project location.
   c. Sometimes, a life cycle cost analysis is performed to select the best combination of additives, mix designs and reclamation methods.
4. *FDR testing*. After the FDR layer is constructed, falling weight deflectometer testing is used to assess the improvement in structural capacity. It is not common to take cores and mechanically test them at various time intervals after construction was completed.
5. *Construction of surface course*. The new FDR base is covered with either an asphalt mixture or concrete surface layer. In some cases, a chip seal application is used.

Although cold-in-place recycling (CIR) and FDR technologies have been used for more than two decades, there are still many unsolved problems that limit their use, in spite of their significant environmental benefits. One key component missing from the general area of pavement preservation is the use of mechanics-based material testing procedures and based on these, the development of performance-based specifications, similar to the approach used for other pavement materials, such as asphalt binders and mixtures.

The aim of this study is to use mechanics-based material testing procedures, MnPAVE simulations, a LCCA and a low temperature performance analysis to evaluate FDR materials. These results will help guide development of performance-based specifications, similar to the approach used for other pavement materials, such as asphalt binders and mixtures.

The proposed research consists of performing indirect tensile (IDT) and dynamic modulus in IDT mode testing on four FDR material mixtures at two different curing times, and using the results to calculate creep stiffness, tensile strength and dynamic modulus values. These values are then used to perform MnPAVE simulations and a Life Cycle Cost Analysis (LCCA) to determine potential performance and design life of each material. Additionally, since MnPAVE only addresses rutting and fatigue cracking, thermal stress calculations are performed to determine critical cracking temperatures for all four materials.

The objective and motivation towards this study were presented in Chapter 1. Chapter 2 provides a literature review of current efforts in the area of FDR. Chapter 3 presents results of a survey conducted to obtain relevant information regarding current FDR practices used by cities and counties of Minnesota. Chapter 4 describes the materials used in the investigation and the testing protocols used to obtain physical and strength properties of the investigated materials. Calculations used to determine properties are presented in Chapter 5. Results of FDR material testing are presented in Chapter 6. Chapter 7 contains numerical simulations conducted in MnPAVE software, using results from Chapter 6. A low temperature performance analysis is provided in Chapter 8. A Life Cycle Cost Analysis is provided in Chapter 9. Chapter 10 provides conclusions and recommendations.

CHAPTER 2: LITERATURE REVIEW

Full-depth-reclamation (FDR) is an in-place rehabilitation process that can be used for reconstruction, lane widening, minor profile improvements, and increased structural capacity by providing a new base layer that is free of defects [1]. FDR technology is becoming popular since it allows improving the service life of pavement structures that require deep rehabilitation at reasonable costs through a relatively simple construction process, conservation of nonrenewable resources, and improvements of existing road grades [2]. In spite of being used for more than 25 years, there are still unsolved issues related to inconsistencies in the quality of materials used and in the technological process.

Efficient quality control, precise specifications and appropriate pulverization methods are recommended to ensure good performance of FDR pavements. For example, a critical issue with FDR stabilized with cement process is balancing strength and performance. Figure 1 below illustrates how increasing the amount of stabilizer may eventually lead to a decrease in performance due to excessive cracking [3].

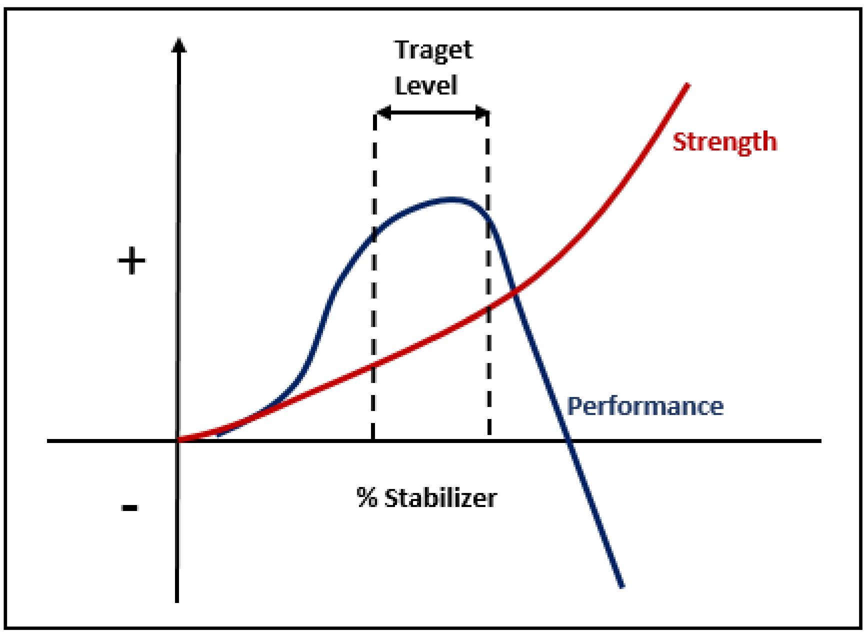

Figure 1: Balance between strength and performance for FDR stabilized with cement [3].

Johanneck and Dai (2013) investigated the responses and performance of stabilized full-depth reclaimed (SFDR) pavements at the Minnesota Road Research Facility [4]. Three SFDR sections were constructed on I-94 and were designed to provide adequate service for a traffic level of 3.5 million ESALs. Falling weight deflectometer (FWD) testing was conducted to determine the layer responses. Pavement distresses such as rutting and cracking have been measured periodically since the sections were opened to traffic. This study focused on the response and performance of interstate highway with high traffic loading. However, some of the observations from this study could be used for SFDR projects in suburban/urban roads as well as local roads.

One example is the increased structural benefit of SFDR layer obtained through a significant reduction of 50% in the horizontal tensile strain at the bottom of the HMA layer over SFDR compared to a traditional structure of HMA over granular base [5].

Dixon et al. (2012) identified construction-related factors that influence the strength of road base treated with cement slurry in conjunction with FDR, and quantified the effects of those factors [5]. They also compared the strength of road base treated with cement slurry with that of road base treated with dry cement. Since conventionally the FDR process involves applying dry cement powder with a pneumatic spreader, which creates undesirable fugitive cement dust, Dixon et al. (2007) proposed using cement slurry to allow cement stabilization in urban areas [5]. The study concluded that if a road base is stabilized with cement slurry in conjunction with FDR, the slurry water batching temperature; the haul time; the environmental temperature; and the presence of a set-retarding, water-reducing admixture will not significantly affect the strength of the cement-treated base (CTB) [5]. This statement is applicable if these factors fall within the limits explored in this research and are applied to a road base with similar properties.

Despite the numerous benefits of cement treatment, FDR in conjunction with conventional cement stabilization is generally not used in urban areas [5]. Various Departments of Transportation have carried out research studies to understand this limitation. The research studies related to FDR performed by Virginia, Georgia, Nevada and Illinois Departments of Transportation are summarized below.

Virginia Department of Transportation (VDOT) completed three trial sections in 2008 where flexible pavements on three primary routes were rehabilitated using FDR incorporating three stabilizing agents [6]. While asphalt emulsion and foamed asphalt were used as stabilizing agent for one section, Portland cement was used for the other two sections. Both laboratory and field evaluation were performed for this study. No statistical difference was observed for laboratory resilient modulus and tensile strength testing between asphalt emulsion and foamed asphalt. Over a 50-year life cycle, VDOT will have an enormous potential saving of primary and secondary network if implementing FDR technology for rehabilitation [6].

Similar to VDOT, Georgia Department of Transportation (GDOT) carried out an investigation on cement-stabilized reclaimed base (CSRB) in full-depth reclamation (FDR) in a project in rural southeast Georgia [7]. CSRB is produced when Portland cement is added to sand–clay base from an FDR, and it is used to underlie hot-mix asphalt. Based on satisfactory results from the pilot FDR project, the Georgia Department of Transportation (GDOT) Office of State Aid has endorsed CSRB as a viable construction option for county contracts. This is because, the majority of Georgia's rural roads are asphaltic concrete underlain by unstabilized bases which consolidate under repeated wheel loading, leading to permanent deformation, or rutting, in the asphaltic concrete surface. FDR using CSRB helps resisting the consolidation, eliminating the rutting in the base and subgrade, reducing moisture susceptibility and using thinner pavement section [7].

Bemanian et al. (2006) in their study explored the successful use of two pavement rehabilitation strategies, cold in-place recycling (CIR) and full-depth reclamation (FDR), by Nevada Department of Transportation (NDOT) [8]. The study mentioned that these strategies have saved NDOT more than $600M over the past 20 years compared with complete reconstruction costs. NDOT uses a 20-year analysis period for rural areas but the user cost in rural areas of Nevada is minimal and was not considered for this analysis in this study. There are four steps NDOT uses in deciding if CIR or FDR are appropriate rehabilitation strategies: 1. Perform an in-depth pavement distress identification survey; 2. Determine the cause of the pavement distress (functional or structural); 3. Perform field testing to check field condition; 4. Perform laboratory testing to produce optimum mix-design procedure [8]. The use of FDR is highly recommended if the pavement is experiencing structural deficiencies. This detailed investigation reflects NDOT's effort in establishing workable cold in-place mix-design procedure and validating structural layer coefficient of 0.26 for use in NDOT's design procedures.
In a project funded by Illinoi Department of Transportation (IDOT), Thompson et al. (2009) evaluated and proposed an implementation procedure of a recently developed cold in-place recycling (CIR) and FDR with Asphalt Products (FDRwAP) technology [9]. The report includes an information and data collection survey which was conducted to identify mixture design procedures. The majority of the projects involving full-depth recycling with asphalt products (FDRwAP) in Illinois are constructed using a stabilizer reclaimer-type machine. A milling operation is also used for projects involving cold in-place recycling with asphalt products (CIRwAP). The study mentioned that the CIR and FDRwAP technology typically results in lower construction costs for flexible pavement reconstruction, rehabilitation, and resurfacing projects. The authors concluded that CIR and FDRwAP have emerged as viable and cost-effective in-place recycling alternative [9].

Syed (2007) in a report of Portland Cement Association (PCA) presented a summary of long-term performance of 75 pavement construction projects conducted in eight states [10]. The report evaluated the performance of FDR with cement process which has been used in these projects. The average project age was 9 years, and the oldest was 26 years. No evidence of premature structural failure was observed in any of the sections, except the distresses in the HMA-overlay. The authors also mentioned that the cost savings of using this process have helped agencies reconstruct 50% to 100% more projects than the conventional remove and replace methods. Some of the problems reported with FDR process were caused by subgrades containing excessive amounts of clay and by cuts made by utility companies after the FDR process was completed. It was also mentioned that more than 60% of the projects were in states with severe cold weather conditions and high potential for winter freeze and spring thaw activity (10). In general, the addition of cement in the FDR process improved the resistance of the reclaimed base to freeze-related road heaving and thaw-related loss in strength. This investigation also provided evidence that FDR with cement pavement sections with sealed shrinkage cracks perform satisfactorily. The rehabilitation of urban sections that have curbs and gutters presents a different challenge. The FDR with cement process adds strength to the underlying material and allows the removal of some pulverized material, allowing the existing profile to remain without adjustment to cross-slope or curb and gutter elevations. Overall, this summary report concluded that FDR with cement process has been a positive experience for agencies in northern areas that have severe weather. The agencies have successfully provided public roads that do not heave in the winters or lose shear strength during spring thaws, and have enhanced road safety. Being cost-effective, this technique has become popular with state, county and city highway agencies attempting to correct their deteriorating pavements and increase the structural capacity of the pavements.

In a project sponsored by MnDOT, Kim et al. (2007) showed that gyratory compaction can be successfully used to prepare FDR specimens for laboratory testing [11]. The materials used to prepare these specimens were collected from County Road (CR) 3 in central Minnesota and Trunk Highway (TH) 5 near St. Paul, Minnesota. The specimens were prepared for various in-situ blends of RAP and crushed aggregates: five different blend types at one density and two moisture contents and one set of replicates. The study concluded that specimens with RAP had greater permanent deformation than the 100% aggregate material and further work was needed to evaluate this phenomenon [11].

Guthrie et al. (2007) investigated the effects of RAP content, RAP type, and base type on the mechanical properties of recycled base materials typical of northern Utah [12]. The strength, stiffness, and moisture susceptibility of laboratory specimens were evaluated in a full-factorial experimental design to fulfill these objectives. The authors stated that utilizing as much RAP as possible reduces pavement reconstruction costs and demonstrates environmental responsibility [12]. The use of high RAP content also reduces the moisture-susceptibility of the materials used. This improvement is needed in areas with high water tables, repeated freeze–thaw cycles, sustained freezing temperatures that lead to frost heave, or poor drainage. The researchers reported that the addition of 25% RAP caused a 29% decrease in strength compared with the neat base material, and the strength declined 13% to 15% with each additional 25% increase in RAP content [12].

In a project sponsored by MnDOT, information regarding best practices, construction techniques, mix design, specifications, and performance of foamed asphalt recycled pavement was summarized [13]. Test sections in Fillmore and Olmsted counties were selected for FWD testing and coring. The FWD data analysis revealed that the recycled pavement layer had a relatively uniform strength, despite the high variability inherent in most low-volume roads. Cores taken from the projects in Fillmore and Olmsted counties indicated that the foamed asphalt layer remains a cohesive unit and does not crumble after coring. Furthermore, laboratory analysis was performed and it was found that overall binder grade may or may not change significantly after the addition of foamed asphalt. The authors mentioned that the mix design is most likely the most critical factor for FDR pavement operations with foamed asphalt because of inherent variations in base thickness. Due to safety concerns related to foam asphalt process, the application of this technology to FDR in urban application is not possible at this time.

One of the most comprehensive laboratory studies on FDR materials was performed by Bocci et al. (2012) on a trial section part of a secondary roadway in Italy [14]. In this study, the mechanical characteristics of the recycled mixture in terms of the evolution of elastic properties, thermo-dependence behavior and resistance to repeated loading was investigated. First, a preliminary survey of the traffic and pavement condition was performed. The tested section was a two-lane low volume road with average traffic volume of 5000 vehicles per day and an equivalent single axel load of 150,000. The pavement condition was "poor" or "very poor" based on pavement condition index (PCI). The original pavement had 8cm of HMA on top of 30 cm of granular material. The FDR process was initiated at the depth of 20 cm from the surface since the granular material below that depth was found to be satisfactory, and the material obtained at the end of the process was a cement-bitumen-treated material (CBTM) consisting of cement and SBS-modified asphalt emulsion. Three different series of specimens were prepared with the materials collected during reconstruction:

1. The first series of CBTM specimens were field compacted and were prepared by means of a mobile shear gyratory compactor (SGC). These specimens were prepared by using the recycled stabilized blend taken in situ immediately after the pulverizing and stabilization operations.
2. The second series of specimens were prepared and compacted in laboratory conditions by mixing the recycled aggregates collected from field with 2% of cement and 4% of SBS-modified bituminous emulsion. Natural moisture content was measured about 5%. The same SGC protocol was followed in this case. Five curing times were used for these specimens: 7, 14, 21, 28, and 35 days. Tests were performed in the following order: dry density tests, indirect tensile stiffness modulus (ITSM) tests after curing, ultrasonic pulse tests (UPT) at different temperatures and finally indirect tensile fatigue test (ITFT) at 20°C.
3. The third series of specimens were cores taken from the pavement, 9 months after the reconstruction. A visual inspection after 9 months under traffic showed no distresses.

All three different sets of specimens were mechanically tested, as previously described. It was found that the analysis of the ITSM results as a function of curing time confirmed the significant role of the curing process on the stiffness properties of CBTM. It was also found that the cores had higher stiffness and also better fatigue resistance than the other two types of specimens, indicating improved performance most likely due to additional curing time and compaction effect of traffic.

CHAPTER 3: SURVEY ON FDR PRACTICE IN URBAN AND SUBURBAN CONDITIONS

A survey was developed and conducted to obtain relevant information about current practice in using FDR for cities and counties in Minnesota. The survey was developed with assistance from the TAP members, and was sent to city and county engineers using the State Aid distribution list. The first survey was sent in February 2015 by email. Based on the limited number of responses, 8 cities and 18 counties, a second survey, that targeted specific issues related to the use of FDR, was distributed in March 2015. Qualtrics computer software was used for the second survey, and 5 cities and 9 counties responded. Five of the 9 counties that responded also responded in the first survey. Both surveys are shown in Appendix 1a and 1b, respectively, at the end of this document.

Overall, 13 cities and 22 counties responded to the surveys. Detailed summaries of the responses received for each question are presented in the following pages. The information received from the two surveys resulted in some important conclusions.

While there is significant interest in using FDR, only a small number of cities and counties have experience with this technology. A few have a very good understanding of the process while others rely entirely on input from consultants. The City of Shoreview has by far the most comprehensive documentation for using FDR in an urban environment. Their "Special Provisions to the 2005 Minnesota Department of Transportation Standard Specifications for Construction" provides very detailed information on construction requirements, method of measurement, and basis of payment for all steps of the FDR process.

For most projects, testing was performed to assess the structural condition of the road before FDR. Testing was performed by two or three engineering companies in the state. The same companies performed the pavement design and material mix design. In a few cases, this was done in house. In most projects, no stabilizing agents were used. In a limited number of projects, additives were used. The most common ones were "Base One" and asphalt emulsion. Laboratory testing was performed on laboratory prepared specimens as part of the material mix design; however, no testing of the placed FDR product was performed to determine if the field product matched the mix design.

All respondents expressed interest in knowing more about FDR and having well-documented guidelines to help them adopt FDR to their roads in cities and counties, which is the main objective of this project.

Most respondents were also interested in potential ideas for improving the current FDR practice. For example, using a mobile cold in place recycling plant could significantly improve the consistency and quality of FDR material. In addition, this procedure would allow using the entire asphalt layer as part of the new base, and instead remove the bottom of the aggregate base, which in many cases is contaminated, to meet strict pavement surface elevation requirements in urban environments. It would also allow for spot subgrade repairs and re-compaction of the upper portion of the subgrade (subgrade preparation) prior to placing the SFDR. An example of a mobile plant that has been successfully used in many projects around the world is the KMA 220 Mobile Cold Recycling Mixing Plant manufactured by Wirtgen.

Of course, this comes with an increase in costs, and therefore, it becomes important to perform a life cycle cost analysis to fully understand the benefits of a more expensive rehabilitation alternative. None of the respondents in the two surveys used “Life cycle analysis” in the selection process. However, many used pavement management tools to trigger FDR.

CHAPTER 4: MATERIALS AND TESTING

The original research plan called for the collection of samples from a few field projects during spring and summer of 2015. However, by the end of August 2015, only one FDR project was identified, on highway 5 in Victoria, and the research team went to the construction site and collected the required materials to prepare laboratory specimens. Since no other projects were identified and to avoid further delays, it was agreed that the research team would test samples prepared in laboratory conditions using different mix designs, rather than wait for new construction projects to collect new materials. The research team has collected large quantities of FDR material (before and after emulsion injection) from the project in Victoria that were used to produce and test other mix designs in addition to the one used in TH5 project. A brief summary of the four mix designs tested is provided in Table 1. Percentages are by total weight of asphalt mixture.

Additional IDT strength at -12ºC and E* testing were performed on FDR materials cured in laboratory conditions to obtain information on the effect of curing time on mechanical properties. Curing times are shown in Table 2.

Table 1: Summary of materials tested

Material Type	Sample ID	Additive	Mix Procedure
Field mixed	FL	3.6% emulsion	field mixed, lab compacted
Lab mixed	LL	3.6% emulsion	lab mixed, lab compacted
Cement Additive	LLC	3.6% emulsion and 1% Portland cement	lab mixed, lab compacted
GNP additive	GNP	3.6% emulsion/graphene blend	lab mixed, lab compacted

Table 2: Curing times for additional testing performed on aged materials

Material Type	Cure Time (months)
Field mixed	12
Lab mixed	4
Cement Additive	2
GNP additive	2

4.1 SAMPLE PREPARATION

The first material, Field mixed, Lab compacted (FL), represents the original FDR mix design used in the construction of the project. The SFDR collected from the field immediately after the injection of the emulsion, was taken to the laboratory and compacted into cylindrical specimens the same day. The mix design provided by AET required using 40 gyrations in the Superpave gyratory compactor.

The dry FDR material, collected from the field prior to emulsion injection, was used to prepare three additional SFDR mixtures in the lab.

The first mixture, Lab mixed, Lab compacted (LL), represents a replicate of the original mix design, except that mixing of the emulsion with the dry FDR material occurred in laboratory conditions. Samples were prepared using dry reclaimed material from TH-5. A test was performed first to determine the water content of the sampled material. Each cylinder was then prepared using 4.7 kg of dry FDR material as follows:

- Place heated (40C) reclaimed material in mixer
- Add 200 milliliters of water to increase total water content to 6.0%
- Mix for one minute
- Allow mixture to rest for four minutes
- Add 180 grams emulsion (3.6% of total material weight)
- Mix for one minute
- Allow mixture to rest for four minutes
- Place 4.75 kg of mixture in the compaction mold
- Compact mixture using 40 gyrations
- Cure at room temperature for at least ten days
- Cut each core into two 38 mm thick samples for mechanical testing

The second mixture prepared in laboratory conditions contained cement and engineered emulsion (LLC). Each cylinder was then prepared using 4.7 kg of dry FDR material as follows:

- Place heated (40C) reclaimed material in mixer
- Add 200 milliliters of water to increase total water content to 6.0%
- Mix for one minute
- Allow mixture to rest for four minutes
- Add 50 grams cement (1.0% of total material weight)
- Mix for one minute
- Heat sample in oven at 40°C for one hour to allow for some cement hydration
- Add 180 grams emulsion (3.6% of total material weight)
- Mix for one minute
- Allow mixture to rest for four minutes
- Place 4.75 kg of mixture in the compaction mold
- Compact mixture using 40 gyrations
- Cure at room temperature for at least ten days
- Cut each core into two 38 mm thick samples for mechanical testing

The third mixture prepared in laboratory conditions contained a graphene nanoplatelet (GNP) additive (Micro850 grade, produced by Asbury Graphite Mills Inc.) and engineered emulsion. Each cylinder was then prepared using 4.7 kg of dry FDR material as follows:

- Place heated (40C) reclaimed material in mixer
- Add 200 milliliters of water to increase total water content to 6.0%
- Mix for one minute
- Allow mixture to rest for four minutes
- Mix emulsion/graphene blend for at least 30 seconds immediately before adding to sample material. This step eliminates any settling of graphene particles
- Add 180 grams emulsion/graphene blend (3.6% of total material weight)
- Mix for one minute
- Allow mixture to rest for four minutes
- Place 4.75 kg of mixture in the compaction mold
- Compact mixture using 40 gyrations
- Cure at room temperature for at least ten days
- Cut each core into two 38 mm thick samples for mechanical testing

For each of the four materials, seven cylindrical specimens were prepared and then cut into fourteen circular 38 mm thick slices for testing. Eleven were tested a few days after cutting. Three slices were kept in storage for testing 9 months after preparation to investigate changes in mechanical properties due to curing.

Creep and tensile strength tests followed procedures outlined in "Standard Test Method for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device," AASHTO T322 -07 [15].

For creep compliance, specimens were loaded diametrically using a vertical constant load of 0.8 kN/sec. Horizontal and vertical deformation were measured using extensometers fixed near the center of the sample. Deformation measurements were then used to calculate creep stiffness. Two replicates were tested for each material at three temperatures, -12°C, 0°C, and 12°C, for a total of 6 tests.

At the end of each creep test, indirect tensile strength tests were performed. Specimens were loaded with a constant rate of vertical deformation until sample failure. Specimen geometry and maximum load were then used to calculate tensile strength.

4.3 DYNAMIC MODULUS

Dynamic modulus is typically measured in compression on cylinders 100 mm in diameter and 170 mm tall [17]. This geometry severely limits the possibility of testing field cores. As a consequence, an alternative method based on the indirect tension (IDT) loading mode (described in detail in reference [18]) was used. The same geometry used for IDT testing, 150 mm in diameter and 38 mm thick, was used to determine dynamic modulus. Frequency sweeps consisting of eight frequencies, ranging from 25 Hz to 0.01 Hz, were performed at 3 temperatures on each replicate: -12°C, 0°C, and 12°C. Three replicates from each material type were tested and |E*| were calculated for each of the 24 temperature and frequency combinations. Average |E*| values were calculated from the three replicates, which were then used to construct master curves using time-temperature superposition principle.

CHAPTER 5: CALCULATIONS

This chapter presents calculations used to obtain stiffness, tensile strength and dynamic modulus results presented in Chapter 6.

Creep compliance is calculated by the following equations, taken from AASHTO Designation T322-07 [15]:

$$D(t) = \frac{\Delta X \times D \times b}{P \times GL} \times C$$

[5.1]

Where:

D(t) = creep compliance at time t (kPa)
△X = horizontal deformation
P = average creep load applied to specimen
b = thickness of specimen (38 mm for all specimens)
D = diameter of specimen (150 mm for all specimens)
GL = gage length

Creep stiffness (S) is the inverse of creep compliance:

$$S = \frac{1}{D(t)}$$

[5.2]

Tensile strength is calculated by the following equation, taken from AASHTO Designation T322-07 [15]:

$$S = (2P)/(\pi bD)$$

[5.3]

Where:

S = tensile stress of specimen
P = failure load for specimen
b = thickness of specimen (38 mm for all specimens)
D = diameter of specimen (150 mm for all specimens)

5.3 DYNAMIC MODULUS

Dynamic modulus was calculated following the procedure described by Kim et al. [18]. First, four integrals were computed based on specimen geometry:

$$F = \int_{-l}^{l} \frac{(1 - x^2/R^2)sin2\alpha}{1 + 2\left(\frac{x^2}{R^2}\right)cos2\alpha + x^4/R^4}dx \quad [5.4]$$

$$G = \int_{-l}^{l} \tan^{-1}\left[\frac{1 - x^2/R^2}{1 + x^2/R^2}tan\alpha\right]dx \quad [5.5]$$

$$M = \int_{-l}^{l} \frac{(1 - y^2/R^2)sin2\alpha}{1 + 2\left(\frac{y^2}{R^2}\right)cos2\alpha + y^4/R^4}dy \quad [5.6]$$

$$N = \int_{-l}^{l} \tan^{-1}\left[\frac{1 + y^2/R^2}{1 - y^2/R^2}tan\alpha\right]dy \quad [5.7]$$

Where x and y are along the horizontal and vertical axes of the specimen, respectively, and:

R = radius of specimen
a = width of load
d = thickness of specimen
l = half of gauge length
α = radial angle of loading = $\sin^{-1}\left(\frac{a/2}{R}\right)$

Dynamic modulus ($|E^*|$) and Poisson's ratio (v) were then computed for each of the 24 temperature and frequency combinations for each of the specimens using the following equations:

$$|E^*| = 2\frac{P_0}{\pi ad}\frac{\beta_1 U_0 - \gamma_1 V_0}{-\beta_2 U_0 + \gamma_2 V_0}$$

$$v = \frac{\beta_1 U_0 - \gamma_1 V_0}{-\beta_2 U_0 + \gamma_2 V_0}$$

Where:

P_0 = amplitude of applied load

U_0 = amplitude of horizontal displacement (averaged between the two sides)
V_0 = amplitude of vertical displacement (averaged between the two sides)

Where P_0, U_0, and V_0 were taken as half of the distance between the smallest and largest values for the last five cycles of loading, and

$\beta_1 = -N - M$
$\beta_2 = N - M$
$\gamma_1 = F - G$
$\gamma_2 = F + G$

CHAPTER 6: RESULTS

In this chapter, results obtained from laboratory testing of both original and aged samples are presented. Stiffness and tensile strength data were obtained from IDT testing (described in section 4.2), and dynamic modulus data were obtained from dynamic modulus testing in IDT mode (described in section 4.3). All calculations used are presented in Chapter 5.

Creep compliance and tensile strength data for individual replicates are presented in Table 3, Table 4, Table 5, and Table 6. Samples denoted with an 'A' or a 'B' are samples cut from the same core sample. Creep stiffness and tensile strength values were averaged for each material and are presented in Table 7 and Table 8.

Table 3: Creep stiffness and tensile strength data for field mixed samples

Sample	Temp °C	Creep Stiffness At 60 sec (GPa)	Creep Stiffness At 500 sec (GPa)	Tensile Strength (MPa)
FL-3	-12	3.324	2.261	0.630
	0	2.104	0.908	
	12	0.518	0.235	
FL-13A	-12	2.471	1.875	0.622
	0	1.304	0.605	
	12	0.266	0.142	
FL-5A	-12	2.946	1.713	0.700
FL-7	-12	2.308	1.479	0.553
FL-1	0	1.205	0.601	0.472
FL-15A	0	1.039	0.509	0.559
FL-5B	12	0.412	0.167	0.312
FL-17A	12	0.418	0.197	0.274

Table 4: Creep stiffness and tensile strength data for lab mixed samples

Sample	Temp °C	Creep Stiffness At 60 sec (GPa)	Creep Stiffness At 500 sec (GPa)	Tensile Strength (MPa)
LL-3	-12	3.225	1.84	
	0	1.096	0.398	
	12	0.213	0.081	0.345
LL-2A	-12	2.356	1.38	
	0	1.117	0.454	
	12	0.263	0.112	0.307
LL-4A	-12	2.21	1.329	0.890
LL-1A	-12	2.33	1.247	0.720
LL-4B	0	0.789	0.279	0.549
LL-6A	0	0.899	0.331	0.630
LL-6B	12	0.182	0.056	0.267
LL-7	12	0.196	0.06	0.270

Table 5: Creep stiffness and tensile strength data for cement additive samples

Sample	Temp °C	Creep Stiffness At 60 sec (GPa)	Creep Stiffness At 500 sec (GPa)	Tensile Strength (MPa)
LLC-4	-12	1.861	1.213	
	0	1.069	0.596	
	12	0.427	0.254	0.260
LLC-6	-12	1.448	1.005	
	0	0.916	0.674	
	12	0.454	0.283	0.259
LLC-3	-12	1.783	1.131	0.359
LLC-7	-12	1.814	1.203	0.411
LLC-1	0	0.977	0.473	0.317
LLC-4B	0	0.959	0.466	0.346
LLC-2	12	0.506	0.268	0.249
LLC-5	12	0.599	0.36	0.276

Table 6: Creep stiffness and tensile strength data for GNP additive samples

Sample	Temp °C	Creep Stiffness At 60 sec (GPa)	Creep Stiffness At 500 sec (GPa)	Tensile Strength (MPa)
GNP-7	-12	2.028	1	
	0	0.613	0.235	
	12	0.111	0.039	0.243
GNP-5B	-12	2.011	1.15	
	0	0.869	0.381	
	12	0.238	0.093	0.414
GNP-1	-12	2.611	1.359	0.720
GNP-6B	-12	2.005	1.228	0.785
GNP-4B	0	0.892	0.358	0.601
GNP-7B	0	0.765	0.323	0.618
GNP-3	12	0.377	0.139	0.282
GNP-4	12	0.219	0.074	0.279

Table 7: Average creep stiffness for all materials

Temp	Time	Field Mixed	Lab Mixed	Cement Additive	GNP Additive
°C	(sec)	(GPa)	(GPa)	(GPa)	(GPa)
-12	60	2.76	2.53	1.73	2.16
	500	1.83	1.45	1.14	1.18
0	60	1.41	0.98	0.98	0.78
	500	0.66	0.37	0.55	0.32
12	60	0.40	0.21	0.50	0.24
	500	0.19	0.08	0.29	0.09

Table 8: Average tensile strength for all materials

Temp	Field Mixed	Lab Mixed	Cement Additive	GNP Additive
°C	(MPa)	(MPa)	(MPa)	(MPa)
-12	0.626	0.805	0.385	0.752
0	0.559	0.589	0.332	0.609
12	0.274	0.297	0.261	0.305

Figure 2, Figure 3, and Figure 4 present creep stiffness curves at -12 °C, 0 °C and 12 °C, respectively. Data from replicate samples were averaged to construct the creep stiffness vs. time curves. Figure 5 presents tensile strength for all materials.

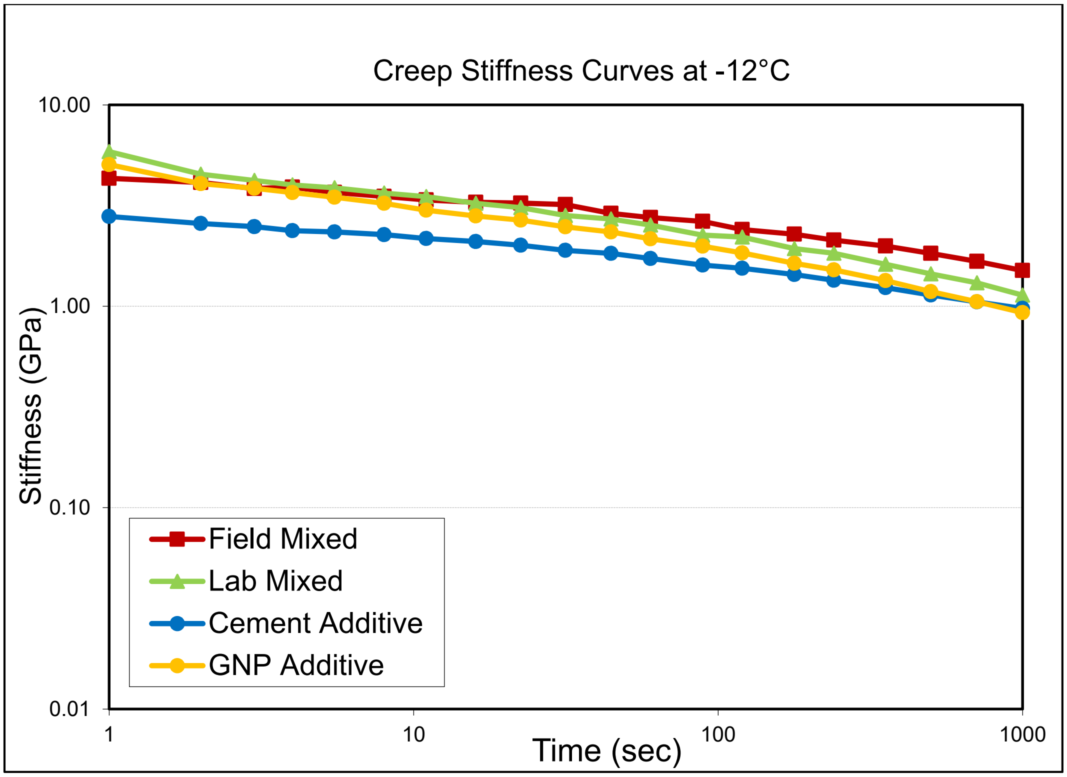

Figure 2: Creep stiffness curves at -12°C for all materials

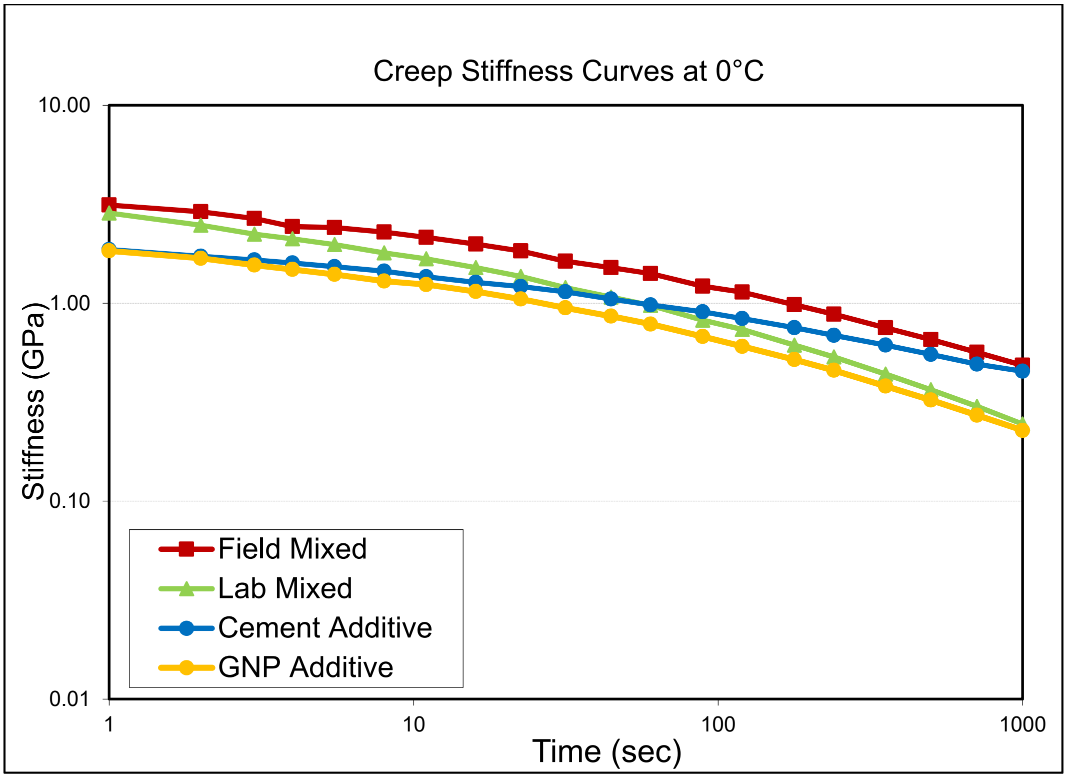

Figure 3: Creep stiffness curves at 0°C for all materials

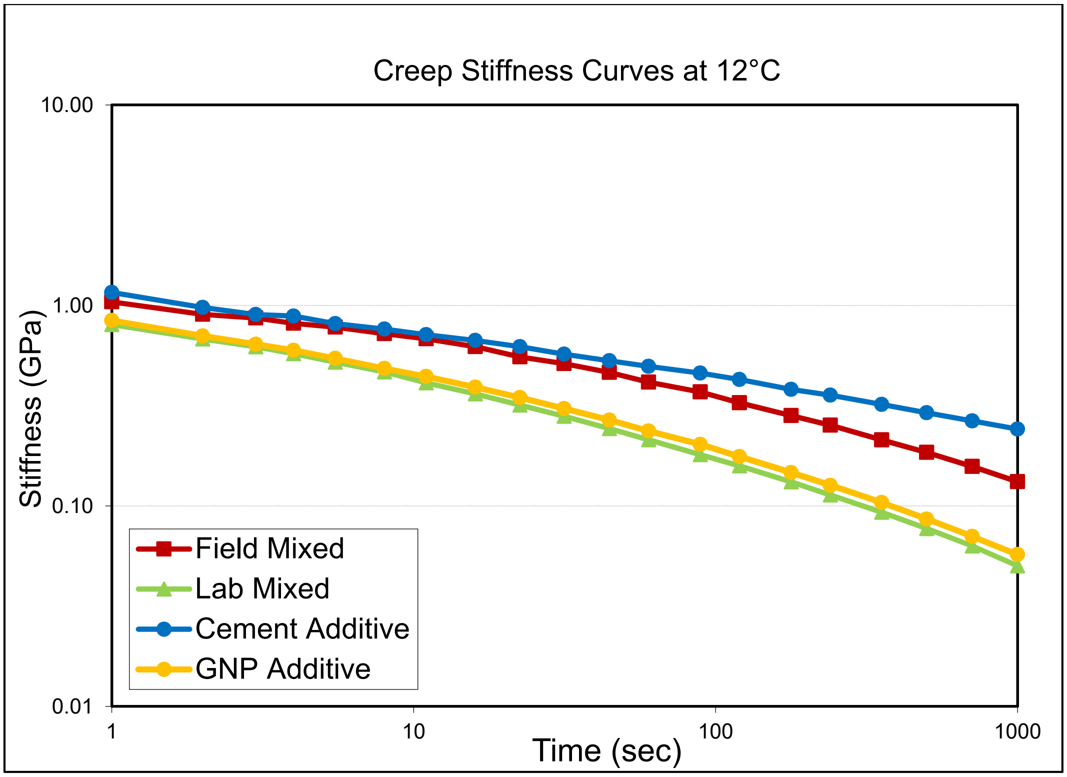

Figure 4: Creep stiffness curves at 12°C for all materials

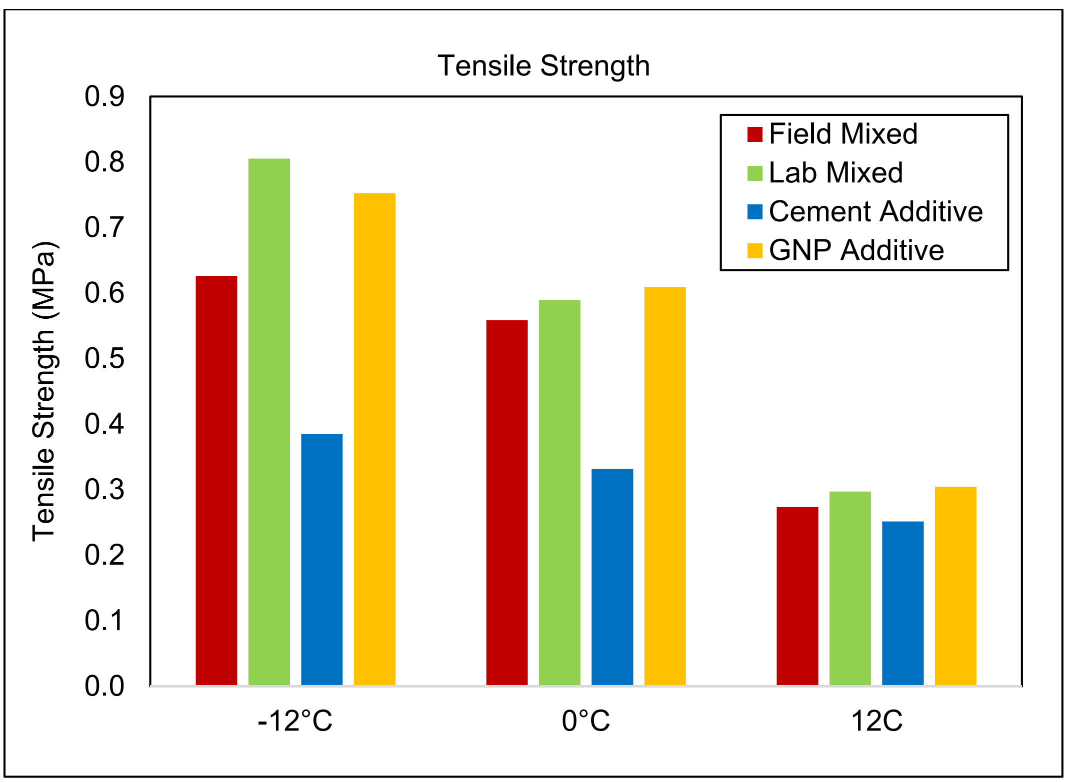

Figure 5: Tensile strength for all materials

A number of conclusions can be drawn from the test results. All four materials behave like viscoelastic materials, similar to asphalt mixtures. The creep stiffness is dependent on temperature and loading time. The field mixed material had higher stiffness and smaller slope (indicator of relaxation properties) compared to the lab mixed materials, especially at the higher temperature. This may be due to a difference in the asphalt emulsion content in the two mixtures. The GNP mixture creep stiffness was similar to the creep stiffness of the lab mixed mixture. The cement treated mixture had the smallest slope of the creep stiffness vs. time curve, indicating reduced relaxation capabilities. It also had the lowest stiffness at the lowest test temperature, and the highest stiffness at the highest test temperature, of all four materials. For tensile strength, the cement treated mix has the lowest strength at -12ºC and 0ºC, and the lab mixed and GNP mix had the highest strength values. At 12ºC, all four mixtures had similar strength values.

Table 9, Table 10, Table 11 and Table 12 contain |E*| values for all three replicates at all 24 temperature/frequency combinations. Average values of |E*| were then used to generate master curves for each of the four mixtures at a reference temperature of 0°C. This was done by fitting the data to the following equation using a procedure proposed by Rowe, et al. [19]:

$$\log|E^*| = \delta + \frac{\alpha - \delta}{1 + e^{\beta+\gamma(log\omega+\log(a(T)))}} \quad [6.1]$$

where:

ω = frequency of load
$a(T)$ = temperature shift parameter
δ, α, β and γ are fitting parameters.

Table 9: Field mixed sample |E*| values for all 24 temperature/frequency combinations

Sample	Temp °C	25 Hz (GPa)	10 Hz (Gpa)	5 Hz (Gpa)	1 Hz (Gpa)	0.5 Hz (Gpa)	0.1 Hz (Gpa)	0.05 Hz (Gpa)	0.01 Hz (Gpa)
FL-13	-12	5.233	6.402	6.056	5.644	5.388	4.727	4.560	3.892
	0	4.659	4.702	4.550	3.782	3.627	2.785	2.659	1.884
	12	2.766	2.613	2.366	2.050	1.913	1.382	1.257	0.318
FL-15	-12	5.005	5.005	5.158	4.744	4.471	4.010	3.696	3.285
	0	4.218	3.953	3.642	3.155	2.886	2.336	2.097	1.630
	12	2.516	2.339	2.027	1.727	1.507	1.092	0.987	0.677
FL-17	-12	3.985	6.402	6.056	5.644	5.388	4.727	4.560	3.892
	0	3.218	2.998	2.653	2.249	2.113	1.757	1.600	1.209
	12	1.965	1.737	1.427	1.224	1.133	0.895	0.800	0.569

Table 10: Lab mixed sample |E*| values for all 24 temperature/frequency combinations

Sample	Temp °C	25 Hz (Gpa)	10 Hz (Gpa)	5 Hz (Gpa)	1 Hz (Gpa)	0.5 Hz (Gpa)	0.1 Hz (Gpa)	0.05 Hz (Gpa)	0.01 Hz (Gpa)
LL-1	-12	6.116	6.421	6.108	5.435	5.100	4.398	4.144	3.269
	0	4.468	4.467	4.086	3.493	3.205	2.528	2.183	1.475
	12	2.888	2.728	2.364	1.722	1.561	1.124	0.907	0.587
LL-2	-12	6.944	6.367	6.338	5.695	5.606	5.031	4.808	3.974
	0	4.856	4.632	4.244	3.733	2.838	2.435	1.979	1.480
	12	3.318	3.282	2.815	2.239	2.016	1.473	1.332	0.687
LL-5B	-12	6.394	5.937	5.687	5.342	5.177	4.454	4.247	3.622
	0	4.881	4.369	4.023	3.370	3.234	2.597	2.330	1.628
	12	3.045	2.685	2.236	1.742	1.577	1.171	0.941	0.577

Table 11: Cement additive sample |E*| values for all 24 temperature/frequency combinations

Sample	Temp °C	25 Hz (Gpa)	10 Hz (Gpa)	5 Hz (Gpa)	1 Hz (Gpa)	0.5 Hz (Gpa)	0.1 Hz (Gpa)	0.05 Hz (Gpa)	0.01 Hz (Gpa)
LLC-2B	-12	2.077	2.737	2.651	2.383	2.312	2.036	1.934	1.615
	0	2.103	1.940	1.851	1.656	1.518	1.261	1.182	0.898
	12	1.386	1.305	1.196	1.077	0.934	0.724	0.681	0.517
LLC-5B	-12	2.116	2.929	2.878	2.894	2.856	2.579	2.476	2.216
	0	2.317	2.201	2.187	1.862	1.755	1.538	1.422	1.094
	12	1.723	1.699	1.563	1.276	1.194	0.934	0.801	0.473
LLC-6B	-12	2.616	3.673	3.478	3.294	3.034	2.748	2.656	2.261
	0	2.658	2.678	2.479	2.162	2.060	1.702	1.453	1.154
	12	1.929	1.942	1.823	1.480	1.361	1.067	1.003	0.785

Table 12: GNP additive sample |E*| values for all 24 temperature/frequency combinations

Sample	Temp	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.05 Hz	0.01 Hz
	°C	(Gpa)	(Gpa)	(Gpa)	(Gpa)	(Gpa)	(Gpa)	(Gpa)	(Gpa)
GNP-2	-12	3.660	5.121	5.002	4.458	4.324	3.655	3.449	2.680
	0	3.796	3.622	3.335	2.774	2.575	1.869	1.645	1.034
	12	2.281	2.097	1.761	1.435	1.187	0.808	0.669	0.369
GNP-3B	-12	4.012	5.745	5.439	5.072	4.861	4.141	3.959	3.132
	0	4.313	4.579	3.825	3.183	2.884	2.296	1.996	1.423
	12	2.165	2.113	1.851	1.423	1.241	0.904	0.740	0.509
GNP-5	-12	3.584	6.220	5.662	5.157	4.786	4.204	3.942	2.991
	0	4.223	4.141	3.625	3.092	2.745	2.088	1.861	1.192
	12	2.400	2.158	2.020	1.462	1.291	0.827	0.730	0.384

|E*| master curves for each material, obtained from fitting average results to the equation on page 11, are shown in Figure 6. Dynamic modulus master curves for individual replicates are shown in Appendix B.

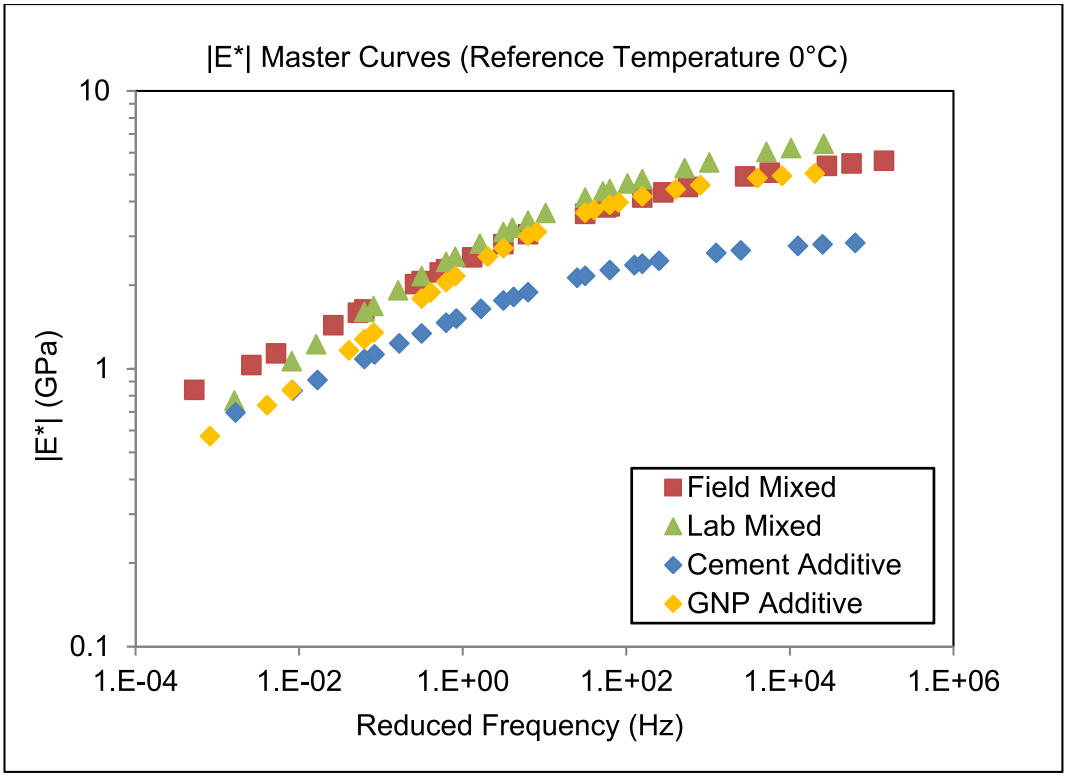

Figure 6: Fitted dynamic modulus master curves for all materials

Similar conclusions to the creep stiffness results can be drawn for the |E*| results. All four materials behave like viscoelastic materials, similar to asphalt mixtures. |E*| is dependent on temperature and on test frequency. The field mixed material had higher modulus at the low and intermediate frequencies and smaller slope (indicator of relaxation properties) compared to the lab mixed materials, especially at the lower frequencies (higher temperature). This again may be explained by a small difference in the asphalt emulsion content in the two mixtures. The GNP mixture |E*| was in general similar to the lab mixed mixture |E*|. The cement treated mixture had the smallest slope of the |E*| vs. time curve, indicating reduced relaxation capabilities. It also had the lowest stiffness at the highest frequencies (lower test temperature).

Tensile strength data for individual aged replicates are presented in Table 13. Average strength values for the original and aged conditions are presented in Table 14 and are plotted in Figure 7. It is observed that cured samples have slightly lower tensile strength than original samples for all materials except GNP additive material. However, the differences are very small and, given the repeatability of the strength test, no clear conclusions can be drawn.

Table 13: Tensile strength data for all aged samples at -12°C

Sample	IDT Strength (Mpa)	Sample	IDT Strength (Mpa)	Sample	IDT Strength (Mpa)	Sample	IDT Strength (Mpa)
FL-3	0.503	LL-3	0.761	LLC-7	0.321	GNP-1	0.765
FL-7	0.623	LL-7	0.770	LLC-X	0.349	GNP-2	0.856

Table 14: Average tensile strength for aged and original samples at -12°C.

Sample Type	Field Mixed	Lab Mixed	Cement Additive	GNP Additive
	(Mpa)	(Mpa)	(Mpa)	(Mpa)
Aged	0.563	0.766	0.335	0.811
Original	0.626	0.805	0.385	0.752
Aged/Original	90%	95%	87%	108%

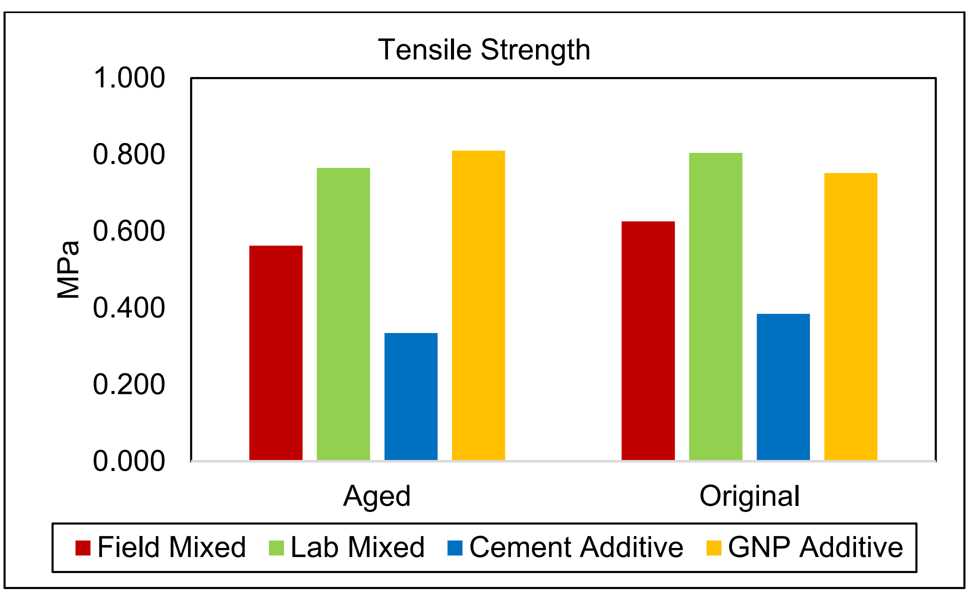

Figure 7: Tensile strength for aged and original materials

6.4 DYNAMIC MODULUS RESULTS FOR AGED SAMPLES

Table 15, Table 16, Table 17 and Table 18 contain |E*| values for all aged replicates at all 24 temperature/frequency combinations.

Table 15: Field mixed aged sample |E*| values for all 24 temperature/frequency combinations

Sample	Temp °C	25 Hz (Gpa)	10 Hz (Gpa)	5 Hz (Gpa)	1 Hz (Gpa)	0.5 Hz (Gpa)	0.1 Hz (Gpa)	0.05 Hz (Gpa)	0.01 Hz (Gpa)
FL-3	-12	4.964	6.710	6.917	6.822	6.541	5.703	5.515	4.568
	0	4.509	4.717	4.335	4.219	3.595	3.056	2.842	2.106
	12	2.593	2.119	2.010	2.138	1.970	1.610	1.527	0.909
FL-7	-12	4.408	5.733	5.595	4.851	4.707	4.240	4.026	3.374
	0	4.372	4.295	3.956	3.524	3.201	2.635	2.327	1.745
	12	2.777	2.625	2.294	1.924	1.665	1.207	1.076	0.618

Table 16: Laboratory mixed aged sample |E*| values for all 24 temperature/frequency combinations

Sample	Temp °C	25 Hz (Gpa)	10 Hz (Gpa)	5 Hz (Gpa)	1 Hz (Gpa)	0.5 Hz (Gpa)	0.1 Hz (Gpa)	0.05 Hz (Gpa)	0.01 Hz (Gpa)
LL-7	-12	4.423	5.277	5.462	4.996	4.664	4.037	3.786	3.213
	0	4.169	3.981	3.655	3.183	2.760	2.183	1.964	1.453
	12	2.664	2.304	1.939	1.472	1.301	0.882	0.788	0.465

Table 17: Cement additive aged sample |E*| values for all 24 temperature/frequency combinations

Sample	Temp °C	25 Hz (Gpa)	10 Hz (Gpa)	5 Hz (Gpa)	1 Hz (Gpa)	0.5 Hz (Gpa)	0.1 Hz (Gpa)	0.05 Hz (Gpa)	0.01 Hz (Gpa)
LLC-7	-12	5.250	4.845	4.717	4.383	4.052	3.631	3.265	2.808
	0	3.308	3.116	3.043	2.505	2.354	2.010	1.847	1.378
	12	33.676	1.911	1.711	1.720	1.469	1.110	0.974	0.777

Table 18: GNP additive aged sample |E*| values for all 24 temperature/frequency combinations

Sample	Temp °C	25 Hz (Gpa)	10 Hz (Gpa)	5 Hz (Gpa)	1 Hz (Gpa)	0.5 Hz (Gpa)	0.1 Hz (Gpa)	0.05 Hz (Gpa)	0.01 Hz (Gpa)
GNP-1	-12	5.453	5.909	5.905	5.358	5.168	4.629	4.179	3.668
	0	4.491	4.347	4.059	3.468	3.293	2.536	2.426	1.765
	12	2.762	2.586	2.259	1.884	1.572	1.173	1.046	0.759
GNP-2	-12	6.041	7.670	7.555	6.798	6.287	5.607	5.193	4.145
	0	5.497	5.733	4.861	4.082	3.791	3.089	2.842	1.866
	12	3.724	3.350	2.655	2.134	1.839	1.313	1.240	0.642

Average values of |E*| were then used to generate master curves for each of the four mixtures at a reference temperature of 0°C. The method used in Task 4 was also used with the experimental data for the cured samples, by fitting the equation below using a procedure proposed by Rowe, et al. [19] :

$$\log|E^*| = \delta + \frac{\alpha - \delta}{1 + e^{\beta+\gamma(log\omega+\log(a(T)))}} \quad [6.2]$$

where:

ω = frequency of load
$a(T)$ = temperature shift parameter
δ, α, β and γ are fitting parameters.

|E*| master curves for the four materials investigated, in both original and cured conditions, are shown in Figure 8, Figure 9, Figure 10, and Figure 11.

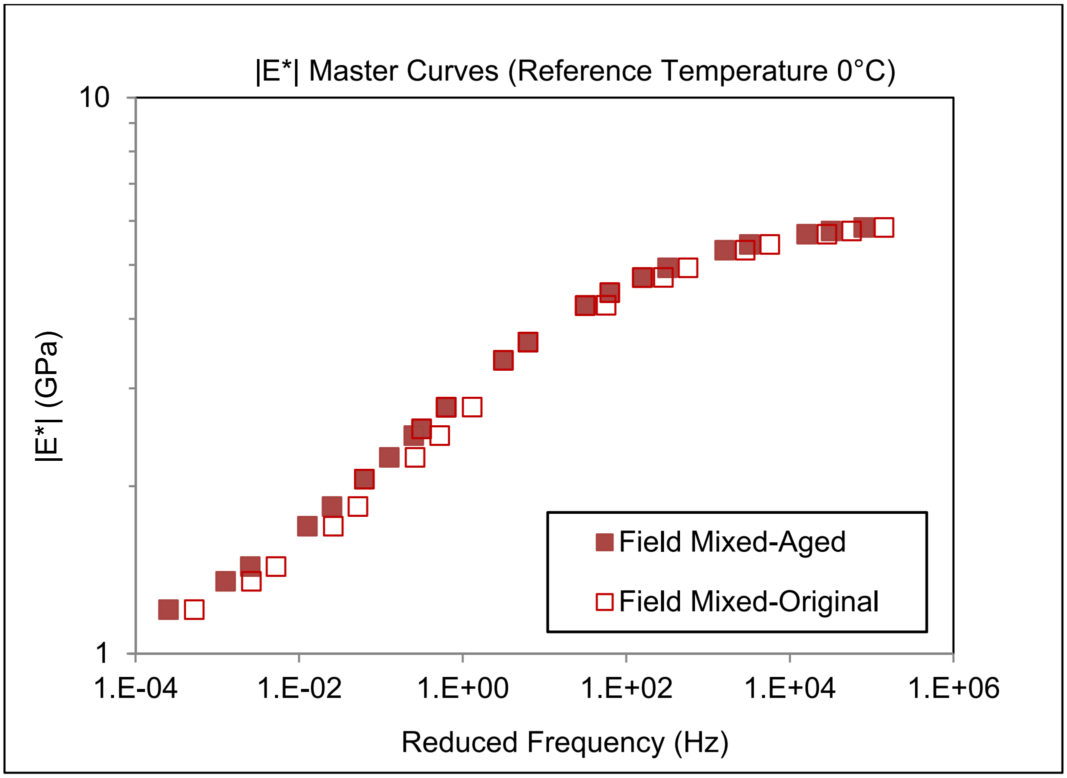

Figure 8: Fitted dynamic modulus master curves for Field mixed samples

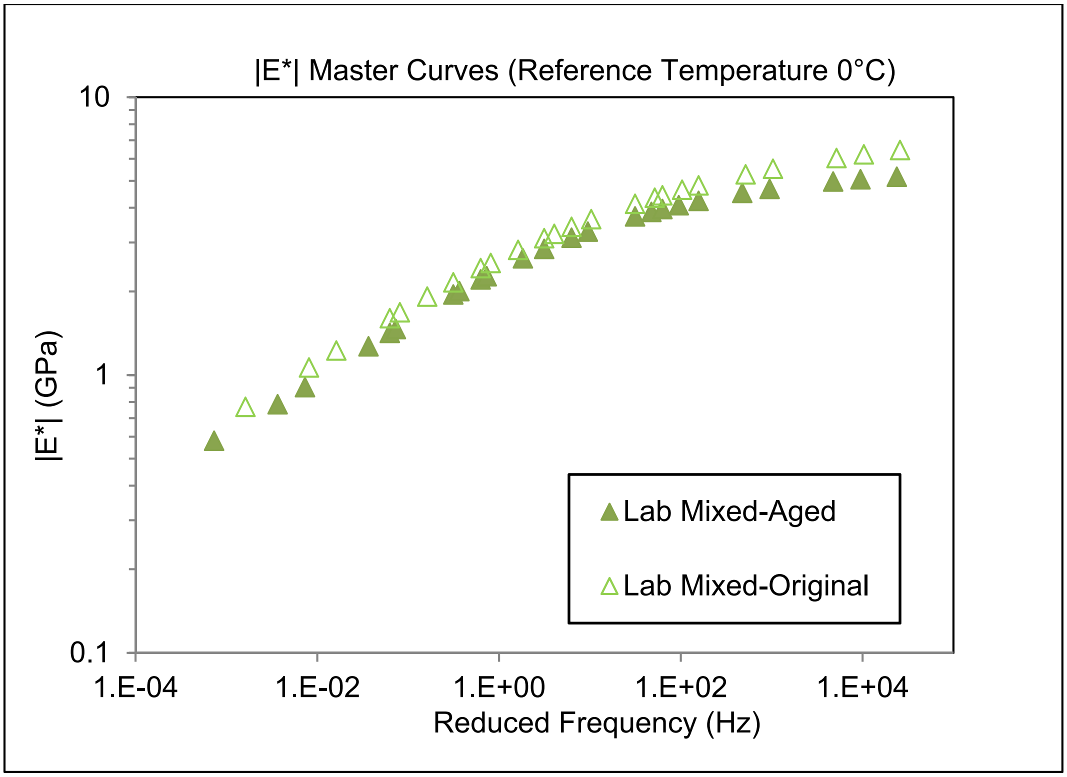

Figure 9: Fitted dynamic modulus master curves for Laboratory mixed samples

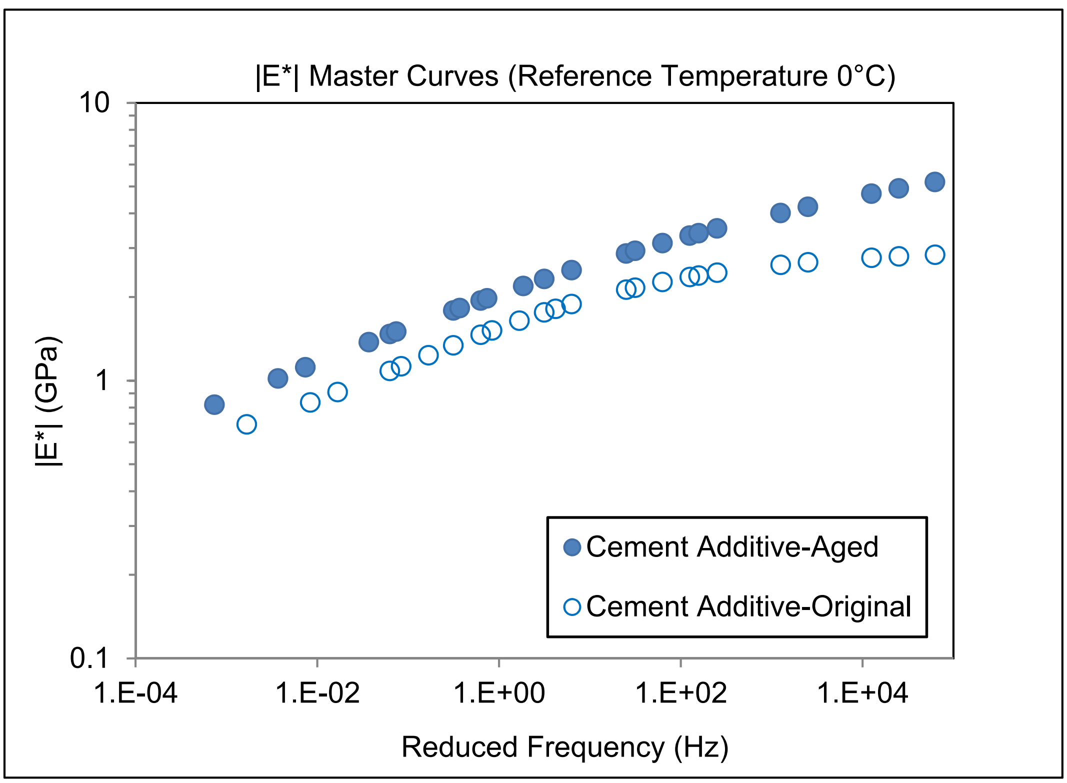

Figure 10: Fitted dynamic modulus master curves for all Cement additive samples

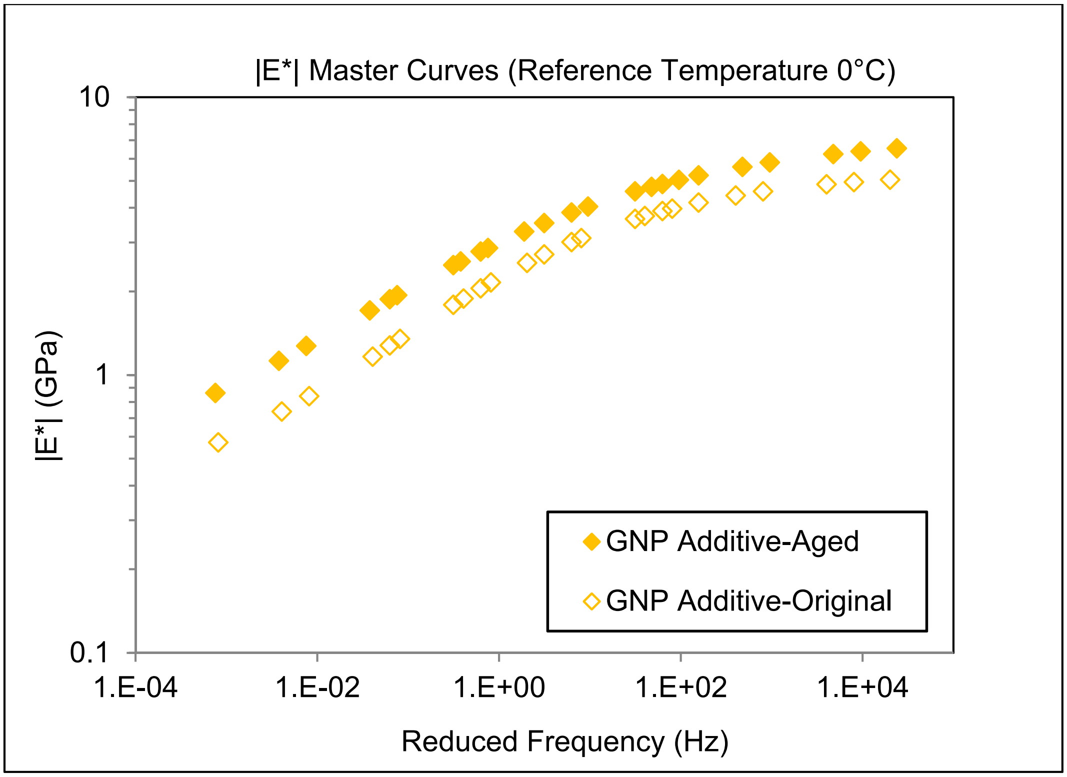

Figure 11: Fitted dynamic modulus master curves for all GNP additive samples

As expected, the |E*| values for the cement treated samples increased significantly with curing time over the entire frequency (temperature) range of the master curve. A similar trend is noticed for the GNP modified samples. For GNP, the increase in modulus was also accompanied by an increase in strength, which could indicate a potential increase in performance. For the Field mixed samples, an increase in modulus is observed at lower frequencies (higher temperature), which is consistent with observations made by others. The opposite trend is observed for the laboratory prepared samples. It is not clear what mechanism is responsible for this behavior.

CHAPTER 7: MNPAVE NUMERICAL SIMULATIONS

MnPAVE is an asphalt pavement analysis program, calibrated for Minnesota conditions, that uses mechanics and empirical relationships to determine pavement design life. For this project, MnPAVE version 6.3 was utilized.

MnPAVE has four input categories: project, climate, traffic and structure.

7.1.1 Project

The project information section requires input of MnDOT district and county. By default, weather data will correspond to the center of the county, unless a more exact location is specified in the climate section.

The project information section also has fields for project number, route, city, reference post, letting date, construction type, designer, soils engineer, and notes. However, these fields are optional and for informational purposes only; they do not affect the analysis results.

7.1.2 Climate

The climate section displays a map of the state of Minnesota with the counties outlined and the MnDOT districts divided by color. The mark on the map defaults to the center of the county specified in the project information section. However, the user can change the location of the analysis either by selecting a different location on the map or by entering latitude and longitude coordinates.

MnPAVE analyzes climate using five seasons: fall (standard), winter (frozen), early spring (base thaw), late spring (soil thaw), and summer (high temperature). Based on the selected location, MnPAVE displays the number of days or weeks in each of the five seasons and the average pavement temperature for that season. Data can also be input manually.

7.1.3 Traffic

MnPAVE has two options for entering traffic: ESAL (equivalent single axle load) and load spectrum. In the load spectrum option, MnPAVE converts the traffic to ESALs during the analysis which significantly increases the computation time so the ESAL option was selected.

For ESAL mode, MnPAVE gives the option to enter lifetime or first year ESALs in millions along with the design period length and the annual growth rate (simple or compound). From this information, it calculates either the lifetime or first year ESALs (whichever was not entered). In addition, the traffic section has input fields for tire and axle information.

7.1.4 Structure

MnPAVE allows the user to input up to five layers, with the last layer being infinite. There is an SFDR option for the second layer, which was used for this research. The user can either select a subtype for each layer or input material properties directly. The user can also select the confidence level desired for the design.

MnPAVE outputs pavement design life for fatigue and rutting. Rutting design life is based on a half inch limit. The design life calculation is limited to a maximum of 50 years. Two analysis options offered: a Quick Reliability simulation and a Monte Carlo simulation, which both return fatigue and rutting reliability data. The reliability level is defined as the probability that the pavement will survive (for example, have less than a half inch of rutting) for the original. The user is able to select the number of cycles for the Monte Carlo simulation. The MnPAVE default of 2500 cycles was used for all simulations in this report. There are also several other output options such as thickness goal seek and quick reliability that were not used for this research.

Simulations in MnPAVE were run for each of the four material types and a control scenario, in order to compare pavement design life.

Carver County was selected and the county center (44° 47’ N, 93° 46’ W) was used as project location. Weather data generated by MnPAVE for this location is provided in Table 19.

Table 19: MnPAVE climate data for TH-5

	Fall	Winter	Early Spring	Late Spring	Summer
Temperature (°F)	48	24	39	59	84
Days	92	90	14	56	113

Traffic was input as 1.995 million lifetime ESALs with a 1.82% simple annual growth rate for a 20-year design period. MnPAVE default values were used for the axle configuration and allowable stress failure criterion sections.

Two pavement structures, the control and SFDR, were input as shown in Figure 12 and Figure 13, respectively. The default confidence level of 70 was used. Default dynamic modulus values from basic mode were used for all layers, except the SFDR layer, which were entered in advanced mode. Figure 12 presents a typical structure used in mill and overlay practice. Default values from basic mode were used in the control simulation. The structure in Figure 13 is based on the MnDOT proposal plan for the SFDR project on TH5, except for one modification: the actual pavement structure has 4” of unstabilized FDR underlain by 7” of Class 5 aggregate base.

Since MnPAVE only allows 5 structural layers, the unstablized FDR was combined with the Class 5 and represented as an 11" aggregate layer. Dynamic modulus values, obtained from the experimental testing, were entered in advanced mode for the SFDR layer, while default values were used for the other four layers.

4" HMA Overlay PG 58-34
Old HMA PG 58-34
8" MnDOT Class 5 Aggregate Base
12" Engineered soil, R-value=12
Undisturbed Soil

Figure 12: Control pavement structure for TH-5

4" PG 58-34 Asphalt
6" SFDR
11" MnDOT Class 5 Aggregate Base
12" Engineered soil , R-value=12
Undisturbed Soil

Figure 13: SFDR pavement structure for TH-5

To input dynamic modulus values into MnPAVE in advanced mode, |E*| values corresponding to the traffic loading frequency is required for each of the five seasons. The frequency is related to the speed limit and it is calculated as follows. First, the loading time is calculated from the following equation, developed by Brown [[21], [22]]:

$$\log t = 0.5d - 0.2 - 0.94 \log v \qquad [7.1]$$

Where:

t = loading time (seconds)

d = pavement depth (meters)
v = vehicle speed (kilometers/hour).

Pavement depth was taken as the combined depth of the asphalt and SFDR layers, a total of 10" for TH-5. Design speed for TH-5 is 55 miles per hour. Using the above equation, the load time was calculated as 0.01249 seconds. Frequency is then calculated as:

$$f = \frac{1}{2\pi t} \quad [7.2]$$

where t is the loading time in seconds and f is the frequency in hertz. A loading frequency of 12.73 Hz was calculated for TH-5.

To determine the |E*| values at 12.73 Hz frequency for all five seasonal average temperatures, it was assumed that the logarithm of the temperature shift factors $\log(a(T))$ varies linearly with temperature, and therefore, individual shift factors could be obtained at each of the five temperatures. Corresponding |E*| values were then calculated and are presented in Table 20.

Table 20: |E*| values used for SFDR layer in MnPAVE (at a frequency of 12.73 Hz)

	Fall	Winter	Early Spring	Late Spring	Summer
	(ksi)	(ksi)	(ksi)	(ksi)	(ksi)
Field Mixed	303.87	240.20	417.86	196.81	88.54
Lab Mixed	351.57	288.35	457.06	241.51	172.72
Cement Additive	194.87	158.60	256.67	133.66	74.20
GNP Additive	287.53	220.74	403.91	175.47	70.58

After $|E^*|$ values were obtained, MnPAVE was used to perform five simulations: one for the control and four for SFDR (one for each material type). Both Quick Reliability and Monte Carlo Reliability analyses were used in the simulations. The results are summarized in Table 21.

Table 21: MnPAVE Results

Material Type	Fatigue Design Life (years)	Rutting Design Life (years)	Quick Reliability Fatigue (%)	Quick Reliability Rutting (%)	Monte Carlo Fatigue Reliability (%)	Monte Carlo Rutting Reliability (%)
Control	>50	18	100	82	99.3	86.8
Field Mixed	>50	32	100	95	100	98.9
Lab Mixed	>50	38	100	97	100	99.7
Cement Additive	>50	29	100	95	100	98
GNP Additive	>50	29	100	95	100	97.6

It can be seen that that both the control and the four versions of SFDR do not fail in fatigue. However, significant differences can be observed for the rutting performance. The traditional mill and overlay structure has slightly more than half the life of the SFDR structure for SFDR material treated with emulsion only.

CHAPTER 8: LOW TEMPERATURE PERFORMANCE

Since MnPave software addresses only rutting and fatigue cracking performance, it was decided to calculate thermal stresses and determine critical cracking temperatures for the four materials investigated. A lower critical temperature is an indication of better thermal cracking performance. A summary of the method used is given below.

Thermal stress that develops as the temperature drops in a restrained uniaxial viscoelastic beam can be calculated using Equation 5.1:

$$\sigma(t) = \int_{-\infty}^{t} \dot{\varepsilon}(t') \cdot E(t-t')dt' \qquad [8.1]$$

Where:

$\sigma(t)$ = time dependent stress

$\dot{\varepsilon}(t') = \dfrac{d\varepsilon(t')}{dt'}$

$E(t-t')$ = relaxation modulus

Taking into consideration that the strain is expresses as:

$$\varepsilon = \alpha \cdot \Delta T \qquad [8.2]$$

Where:

α = coefficient of thermal expansion or contraction;

ΔT = temperature change

and that the reduced time (ζ) expressed as:

$$\xi = \frac{t}{a_T} \qquad [8.3]$$

Where:

t = time, sec;

a_T = shift factor

then equation [2.11] can be written as:

$$\sigma(\xi) = \int_{-\infty}^{\xi} \frac{d\varepsilon(\xi')}{d\xi'} \cdot E(\xi-\xi')d\xi' = \int_{-\infty}^{t} \frac{d(\alpha\Delta T)}{dt'} \cdot E(\xi(t)-\xi'(t))dt' \qquad [8.4]$$

Where:

$E(\xi - \xi')$ = relaxation modulus;
$\varepsilon(\xi')$ = strain

To calculate thermal stress, the following procedure is used:

1. Creep compliance is obtained from IDT experiments, as previously described.

2. Relaxation modulus E(t) is calculated from IDT creep compliance using Hopkins and Hamming numerical algorithm (1957).

3. Relaxation modulus E(t) master curve is obtained using CAM model (Marasteanu and Anderson, 1996):

$$E(t) = E_g \cdot \left[1 + \left(\frac{t}{t_c} \right)^v \right]^{-w/v} \quad [8.5]$$

Where:

E_g = Glassy modulus;
T_c, v and w = parameters in the model

The shift factor expression is:

$$a_T = 10^{C_1 + C_2 \cdot T} \quad [8.6]$$

Where:

C_1 and C_2 = parameters;
T = reference temperature, ºC

4. The one-dimensional hereditary integral equation (Equation [8.4]) is solved numerically using Gaussian quadrature with 24 Gauss points. It is assumed that the cooling rate is 1ºC per hour.

5. The IDT strength at all three temperatures is plotted and the intersection of the strength vs. temperature curve and thermal stress curve gives the critical cracking temperature.

An example is shown in Figure 14.

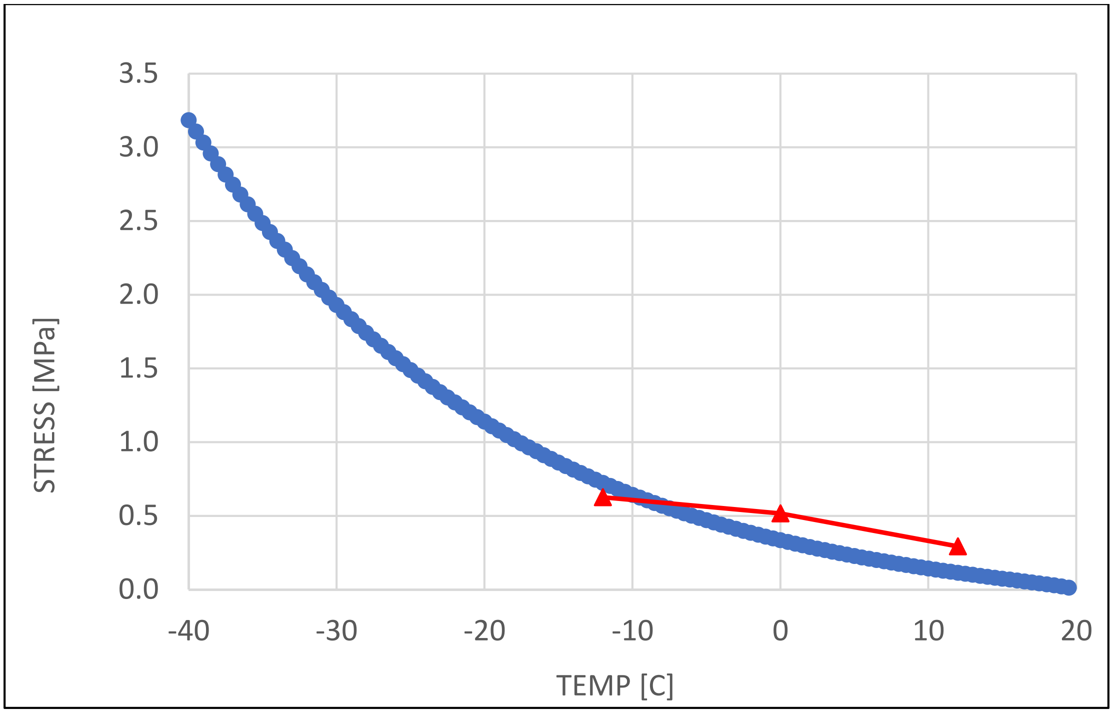

Figure 14: Thermal stress and IDT strength results for lab prepared, lab compacted samples

The results indicate a slightly lower cracking temperature for the FDR material with GNP and a higher cracking temperature for the FDR material with cement.

CHAPTER 9: LIFE CYCLE COST ANALYSIS

A LCCA is used to evaluate alternative road designs and determine which is the most cost-effective. In this section, LCCA was used to compare the four FDR material options and a traditional mill and overlay option.

The LCCA followed MnDOT procedures outlined in the MnDOT Pavement Design Manual [23]. Two spreadsheets, both developed by MnDOT and updated in July of 2016, were used. The first, *Initial_Estimate_D5_7_12_16,* is designed to sum all initial construction costs for each potential road design being considered for a particular project. The second, *MnLCCA_D5_7-12-16*, requires the input of the initial estimate costs, then adds maintenance schedule costs for each design, outputting a summary that allows for comparison of all designs being considered.

Five designs were considered in the LCCA; one for each type of material tested (described in Chapter 4), plus a mill and overlay design, which is considered as a 'control.'

The initial estimates were created as follows:

1. An example provided by Steven Henrichs, MnDOT Assistant Pavement Design Engineer, was used to determine the items needed for initial construction of a mill and overlay design, and road dimensions were changed according to the TH5 plan specifications (mainline width of 24 feet, shoulder width of 8 feet, two lanes and two shoulders).
2. The FDR initial estimates were created by taking line items from Option 3 of the original LCCA used during TH5 planning. These items were added to the initial estimate file, which contains current 2016 prices for all items. Currently, the file contains three discrepancies:
    a. The original LCCA did not contain a line item for milling any of the existing road, but a line item was added to the current LCCA.
    b. The original LCCA contained a line item for "Bituminous Material for Mixture," with a cost of $725 per ton, 138 tons needed for a total cost of $99,982. This item is not an option in the current file (*Initial_Estimate_D5_7_12_16*).
    c. The original estimate listed 'Type SP 12.5 Wearing Coarse Mixture,' but did not specify which mixture. The TH5 plan specifications listed type '3C,' which was therefore used in the current LCCA.
3. The initial estimates for SFDR with either cement or GNP additive were made by adding $3,086 per mile for the cost of cement and $34,452 per mile for the cost of GNP.

Once initial estimates were created, they were entered into the *MnLCCA_D5_7-12-16* file as five alternates. Each alternate requires additional information, including pavement type, lane and shoulder widths, BESAL information, thickness of top lift, and which HMA mixtures were used. Once this information is input, a 35 year HMA maintenance schedule is automatically generated.

Design life is specific to the pavement type, and cannot be changed (for an SFDR, life is 20 years, for a mill and overlay design life is either 13-17 years or >17 years). Therefore, in order to consider the design life calculated by MnPAVE for each alternate design, the maintenance schedule must be manually changed.

For example, the FDR design based on Field mixed material, the MnPAVE simulation found the rutting design life to be approximately 32 years. Since the LCCA file assumes 20 years, all maintenance was shifted down by twelve years (for instance, the first maintenance task is ‘crack treatment.’ Originally it was scheduled for 8 years, but was then shifted down to occur at 20 years). Additionally, the remaining life must be manually calculated. For the FDR design, the last mill and overlay occurs at 32 years. Since a mill and overlay has a design life of 17 years, 14 years of life still remain on the pavement at 35 years. Therefore, the remaining life is calculated by multiplying the cost of the mill and overlay by 14/17, then subtracted from the total. These steps were then repeated for the other three FDR design options (Lab mixed, Cement additive and GNP additive), with their respective rutting design lives.

For the mill and overlay, the HMA schedules included in the spreadsheet are accurate so no adjustment was made for design life. The design life option of 13-17 years was used.

Initial Costs for the control option (mill and overlay) are shown in Table 22. Initial costs for SFDR stabilized with emulsion only are shown in Table 23. Initial costs for SFDR with cement and GNP additives differ by $3,086 per mile for the cost of cement and by $34,452 per mile for the cost of GNP), respectively; all line items are the same as Table 23. Maintenance schedules and cost summaries for all five options are presented in Figure 15, Figure 16, Figure 17, Figure 18 and Figure 19.

Equivalent uniform annual costs shown in the last line of each schedule are summarized and presented in Figure 20.

Table 22: Initial costs for placement of one mile of mill and overlay (control)

Specification - Description	Depth (in)	Width (ft)	Quantity (mile)	Unit	Unit Price	Cost (mile)
2232501/00050 - MILL BITUMINOUS SURFACE (2.0")	2	40	23466.7	SY	$1.01	$23,679.17
2360501/23200 - TYPE SP 12.5 WEARING COURSE MIXTURE (3,B)	2	24	1591.0	TON	$56.99	$90,678.93
2360501/23200 - TYPE SP 12.5 WEARING COURSE MIXTURE (3,B)	1.5	40	1988.8	TON	$56.99	$113,348.67
2118501/00010 - AGGREGATE SURFACING CLASS 1	2	3	178.2	TON	$25.00	$4,455.00
					Cost/Mile:	**$232,161.77**

Table 23: Initial costs for placement of one mile of FDR using material stabilized with emulsion only

Specification - Description	Depth (in)	Width (ft)	Quantity (mile)	Unit	Unit Price	Cost (mile)
2232501/00050 - MILL BITUMINOUS SURFACE (2.0")	2	40	23466.7	SY	$1.01	$23,679.17
Stabilized Full Depth Reclamation (SFDR)	8	24	112640.0	SY-in	$0.88	$98,851.10
2360502/23300 - TYPE SP 12.5 NON WEARING COURSE MIXTURE (3,C)	2	24	1591.0	TON	$53.92	$85,784.36
2353504/00010 - ULTRATHIN BONDED WEARING COURSE	5/8	24	14080.0	SY	$6.05	$85,157.94
2360501/23300 - TYPE SP 12.5 WEARING COURSE MIXTURE (3,C)	2	16	1060.7	TON	$63.65	$67,510.74
2118501/00010 - AGGREGATE SURFACING CLASS 1	2	3	178.2	TON	$25.00	$4,455.00
					Cost/Mile:	**$365,438.32**

Year	Activity	Cost	Pres. Cost/per Mile
0	2" ML Mill & Fill and 1.5" Full width Overlay	$ 232,161.77	$ 232,161.77
1			$ -
2			$ -
3	Crack Treatment	$ 2,534.40	$ 2,417.97
4			$ -
5			$ -
6			$ -
7	Seal	$ 11,520.89	$ 10,323.54
8			$ -
9			$ -
10			$ -
11			$ -
12			$ -
13			$ -
14			$ -
15			$ -
16			$ -
17	ML Overlay 3.5"	$ 233,196.02	$ 178,641.19
18			$ -
19			$ -
20	Crack Treatment	$ 2,534.40	$ 1,852.30
21			$ -
22			$ -
23			$ -
24	Seal	$ 11,520.89	$ 7,908.41
25			$ -
26			$ -
27			$ -
28			$ -
29			$ -
30			$ -
31			$ -
32			$ -
33	ML Overlay 4.0"	$ 259,860.65	$ 154,906.50
34			$ -
35	Remaining Life	$ (225,212.56)	$ (130,108.39)
LCCA - Net Present Cost/ per Mile			$ 458,103.27
Maintenance - Net Present Cost/per Mile			$ 225,941.50
Net Present Cost for Segment			$ 458,103.27
Maintenance - Net Present Cost for Segment			$ 225,941.50
Equivalent Annual Cost			17,140.11

Figure 15: Maintenance schedule for mill and overlay (control). Initial estimate was entered into year 1, and schedule was automatically generated.

Year	Activity	Cost/per Mile	Pres. Cost/per Mile
0	6" SFDR, 2.5" HMA, 5/8" UTBWC	$ 365,438.00	$ 365,438.00
1			$ -
2			$ -
3			$ -
4			$ -
5			$ -
6			$ -
7			$ -
8			$ -
9			$ -
10			$ -
11			$ -
12			$ -
13			$ -
14			$ -
15			$ -
16			$ -
17			$ -
18			$ -
19			$ -
20	Crack Treatment	$ 1,267.20	$ 926.15
21			$ -
22			$ -
23			$ -
24	Seal	$ -	$ -
25			$ -
26			$ -
27			$ -
28			$ -
29			$ -
30			$ -
31			$ -
32	ML Mill 3.0"	$ 299,480.02	$ 181,344.83
33			$ -
34			$ -
35	14/17 Remaining Life	$ (246,630.60)	$ (142,481.89)
LCCA - Net Present Cost/ per Mile			$ 405,227.09
Maintenance - Net Present Cost/per Mile			$ 39,789.09
Net Present Cost for Segment			$ 405,227.09
Maintenance - Net Present Cost for Segment			$ 39,789.09
Equivalent Annual Cost			15,161.72

Figure 16: Maintenance schedule for Field mixed SFDR design. Initial estimate was entered into year 1, and schedule was manually changed to account for a rutting design life of 32 years.

Year	Activity	Cost/per Mile	Pres. Cost/per Mile
0	6" SFDR, 2.5" HMA, 5/8" UTBWC	$ 365,438.00	$ 365,438.00
1			$ -
2			$ -
3			$ -
4			$ -
5			$ -
6			$ -
7			$ -
8			$ -
9			$ -
10			$ -
11			$ -
12			$ -
13			$ -
14			$ -
15			$ -
16			$ -
17			$ -
18			$ -
19			$ -
20			$ -
21			$ -
22			$ -
23			$ -
24			$ -
25			$ -
26	Crack Treatment	$ 1,267.20	$ 843.01
27			$ -
28			$ -
29			$ -
30	Seal	$ -	$ -
31			$ -
32			$ -
33			$ -
34			$ -
35	Remaining Life	$ -	$ -
LCCA - Net Present Cost/ per Mile			$ 366,281.01
Maintenance - Net Present Cost/per Mile			$ 843.01
Net Present Cost for Segment			$ 366,281.01
Maintenance - Net Present Cost for Segment			$ 843.01
Equivalent Annual Cost			13,704.54

Figure 17: Maintenance schedule for Lab mixed SFDR design. Initial estimate was entered into year 1, and schedule was manually changed to account for a rutting design life of 38 years.

Year	Activity	Cost/per Mile	Pres. Cost/per Mile
0	6" SFDR, 2.5" HMA, 5/8" UTBWC	$ 368,524.08	$ 368,524.08
1			$ -
2			$ -
3			$ -
4			$ -
5			$ -
6			$ -
7			$ -
8			$ -
9			$ -
10			$ -
11			$ -
12			$ -
13			$ -
14			$ -
15			$ -
16			$ -
17	Crack Treatment	$ 1,267.20	$ 970.75
18			$ -
19			$ -
20			$ -
21	Seal	$ -	$ -
22			$ -
23			$ -
24			$ -
25			$ -
26			$ -
27			$ -
28			$ -
29	ML Mill 3.0"	$ 299,480.02	$ 190,077.10
30			$ -
31			$ -
32			$ -
33			$ -
34			$ -
35	14/17 Remaining Life	$ (193,781.19)	$ (111,950.06)
LCCA - Net Present Cost/ per Mile			$ 447,621.87
Maintenance - Net Present Cost/per Mile			$ 79,097.79
Net Present Cost for Segment			$ 447,621.87
Maintenance - Net Present Cost for Segment			$ 79,097.79
Equivalent Annual Cost			16,747.94

Figure 18: Maintenance schedule for Cement additive SFDR design. Initial estimate was entered into year 1, and schedule was manually changed to account for a rutting design life of 29 years.

Year	Activity	Cost/per Mile	Pres. Cost/per Mile
0	6" SFDR, 2.5" HMA, 5/8" UTBWC	$ 399,890.08	$ 399,890.08
1			$ -
2			$ -
3			$ -
4			$ -
5			$ -
6			$ -
7			$ -
8			$ -
9			$ -
10			$ -
11			$ -
12			$ -
13			$ -
14			$ -
15			$ -
16			$ -
17	Crack Treatment	$ 1,267.20	$ 970.75
18			$ -
19			$ -
20			$ -
21	Seal	$ -	$ -
22			$ -
23			$ -
24			$ -
25			$ -
26			$ -
27			$ -
28			$ -
29	ML Mill 3.0"	$ 299,480.02	$ 190,077.10
30			$ -
31			$ -
32			$ -
33			$ -
34			$ -
35	14/17 Remaining Life	$ (193,781.19)	$ (111,950.06)
LCCA - Net Present Cost/ per Mile			$ 478,987.87
Maintenance - Net Present Cost/per Mile			$ 79,097.79
Net Present Cost for Segment			$ 478,987.87
Maintenance - Net Present Cost for Segment			$ 79,097.79
Equivalent Annual Cost			17,921.51

Figure 19: Maintenance schedule for GNP additive SFDR design. Initial estimate was entered into year 1, and schedule was manually changed to account for a rutting design life of 29 years.

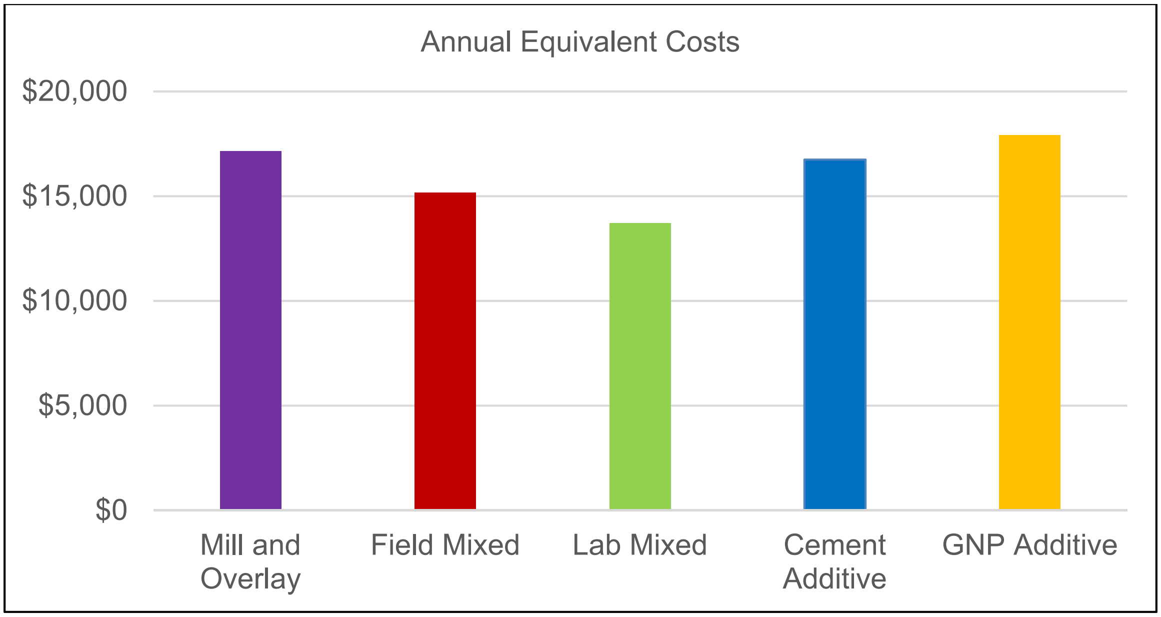

Figure 20: Comparison of annual equivalent costs for all designs.

Based on the limited test data obtained in this investigation and on predicted pavement life using MnPAVE, it can be concluded that for a 35-year analysis, the FDR alternative provides a more effective way of rehabilitating the pavement than a traditional mill and overlay. The addition of cement brings the equivalent annual costs for FDR to similar values to mill and overlay, while the use of GNP makes the cost slightly higher.

CHAPTER 10: CONCLUSIONS AND RECOMMENDATIONS

At this time, it is not possible to provide preliminary guidelines for the selection process due to the limited scope of this work. However, a number of useful conclusions can be drawn at the end of this investigation:

- Full depth reclamation materials can be successfully tested using mechanical testing methods used for asphalt mixtures.
- The material parameters obtained in these tests can be used with pavement design software to predict the pavement life of various pavement rehabilitation scenarios.
- Based on predictions made using MnPAVE software and on life cycle costs analysis over a period of 35 years using MnDOT calculations spreadsheets, it appears that FDR can be a more cost effective method than the traditional mill and overlay. This conclusion needs to be further validated with additional FDR materials and with additional historical performance data from FDR projects.
- The addition of cement reduces the predicted life and increases the critical cracking temperature of FDR materials, while slightly increasing the initial costs.
- The addition of GNP also reduces the predicted life, but it also reduces the critical cracking temperature, an indication of better cracking resistance. The initial cost increases by a significant amount making it the most expensive scenario.
- The field samples compacted in laboratory conditions had better mechanical properties than the field compacted samples, which may suggest that compaction in the field can be improved.
- Curing has a positive effect on the FDR materials with cement and GNP additives; for both materials, the dynamic modulus increased. The GNP samples also had a slight increase in tensile strength.
- Results regarding curing effects for Lab mixed and Field mixed samples are inconclusive, and may require further testing.

These preliminary results indicate that SFDR represents a viable solution for extending the life of pavement structures. It should be noted that this analysis does not include user costs associated with any rehabilitation activities, which makes the SFDR scenario even more attractive since the mill and overlay needs to be rehabilitated after 18 years.

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[26] 23 Rowe, G. M., Khoee, S. H., Blankenship, P. and Mahboub, K. C. (2009). Evaluation of Aspects of E* Test by Using Hot-Mix Asphalt Specimens with Varying Void Contents. *Transportation Research Record*, 2127: 164 – 172

APPENDIX A
SURVEY RESULTS

A. Location

Information was collected from the following cities and counties:

13 cities:

City	County
Brainerd	Crow Wing
Burnsville	Dakota
Champlin	Hennepin
Columbia Heights	Anoka
Marshall	Lyon
Mankato	Blue Earth
Northfield	Rice

City	County
Oakdale	Washington
Rochester	Olmsted
Sartell	Benton
Shoreview	Ramsey
Thief River Falls	Pennington
Woodbury	Washington

22 counties:

Beltrami	Itasca	Nobles	Red Lake	Wilkin
Cass	Lake	Olmsted	Rice	Wright
Dodge	McLeod	Pennington	Rock	
Filmore	Mille Lacs	Polk	Steele	
Goodhue	Morrison	Pope	Stevens	

B. Experience with FDR process

1. How many FDR projects did you have during the last 10 years?

Number of FDR projects	0	1-3	4-10	More than 10
Number of cities	2	6	5	
Number of counties	4	8	5	5

2. Total FDR length/ county

Total length/city	0	<30 miles	30-50 miles	>50 miles
Number of cities	2	7	3	
Number of counties*	4	8	5	5

3. What tests were used to assess the structural condition of the base under the FDR layers?

City:

- SPT, and cores
- Cores were taken approximately every 1000 feet
- N/A

County:

- None
- N/A
- Test rolling
- FWD Testing
- Relied on material GE from original typical section
- Coring
- Used past typical sections to determine base under FDR and CIR layers.
- N/A

4. **What was used for the pavement surface?**

Pavement surface	Asphalt overlay	Asphalt overlay + chip seal (2 years later)	Chip seal
Number of cities*	7		
Number of counties*	13	1	1

5. **If an additive was used, what was it, and how was the specific additive selected?**

Type of additive

Type of additive	Cities* that used this type	Counties*that used this type
Base one		3
Type C fly ash		1
Fly ash		1
CSS-1h		1
MS250		1
HFMS2		1

Asphalt emulsion	1	2
Cement	1	
Class 5		1

Additive selection based on

City:

- information and past experience
- N/A

County:

- cost and past experience (3)
- contractor (1)
- trial and error (1)
- cost (2)
- engineering analysis based on existing road material (1)
- Lake County Highway Department. no additives for CIR except water. class 5 added to some of our reclamations
- N/A

6. Who performed the FDR design?

City:

- In house (3)
- Consultant
- American Engineering and Testing (3)
- Consultant engineer Bolton & Menk. They used the MnDOT pavement design spreadsheet. The reclaimed material was left in place without additives and was assume as gravel GE in the road section design.
- Michael McCarty. GE method was used for the two cement stabilized project. Spectra pave 4 pro from Tensar was used for the two with trix geo grid.
- In house. Pavement design based on ESAL's
- N/A

County:

- I performed the pavement design using historical information inputted into a computer program to make sure we met the ten ton design. St. Louis County's GE Calculator and State Aids GE Calculator.
- In house (8)
- In house using Gravel Equivalency (GE) method
- Consultant (2)
- American Engineering and Testing (3)
- No design (50/50 Rap to aggregate) (1)
- Braun Intertec and Beltrami County. R-Value/GE nomograph
  - Mn/pave
  - Lake County Highway Department, CIR mix design in proposal for contractor to follow
  - N/A

7. Was the top layer milled and removed or was it used in the FDR mixture?

	Used in FDR	Milled and removed	Partially used
City*	7		1
County*	7	1	5

8. How did you check that the FDR material placed on the road matched the properties of the material tested in the lab? In other words, do you have a quality control process for FDR projects?

City:

- No quality control process
- Sampled materiel. Gradations and cylinders (in the case of the cement stabilized materiel)
- N/A

County:

- No quality control process (3)

- Density was verified on the material and gradations were conducted to ensure the material met specifications for aggregate base class 6
- For the 2008 project we worked closely with the consultant to walk us through there process to make sure we were getting the correct product because we have not done anymore we have not developed a testing routine.
- Did gradations and moistures on both the class 5 and the blended mixture; did cores and mix gradations for CIR.
- N/A

C. <u>FDR selection process</u>

1. What are the top pavement conditions/distresses for which you would consider FDR as the top rehabilitation choice?

City:

- Poor condition, cracking and deterioration
- 25 to 55 years old
- Distress w/o subgrade failure
- Cracks longitudinal and transversal
- Cracking, spalling, isolated areas with permanent failure
- Multiple patches

County:

- Block cracking, alligator cracking, reflective cracking
- Poor ride

- Rutting
- Raveling
- Severe pavement deterioration and low roadway base strength.
- Failed pavement beyond the point where a concrete overlay or asphalt overlay would be effective
- Old thin bituminous with severe cracking

2. Do you have a pavement management system that includes triggers for the use of FDR, such as percent and severity of surface cracking, road widening, etc?

City:

- Our typical sections are adequate for a perpetual design. We have had great success with reclamation. We specify a class 5 gradation, which gives us a stable base and excess product to utilize on other city projects.
- Thin existing bituminous pavement. Local streets were constructed with 2 inches of bituminous pavement and extensive cracking.
- FDR with emulsion stabilizes the road bed and eliminates reflective cracking, which is not accomplished by a mill and overlay. The equipment required for FDR is small enough to be used on residential streets as opposed to the large trains required for cold or hot in-place recycling
- The added life to the existing road. Typically our City Streets are not built with a big enough asphalt section to consider a mill and overlay. We've tried a few 1-1/2" mill and overlays on our smaller asphalt sections (3.5") and the reflective cracking appears immediately, and we feel we are not getting the expected life cycle we after.
- Selection based on exiting typical section, road condition, and available budget
- We use it on rural section roadways and on urban section roadways where base grading and the roadway crown need to be rebuilt
- No. We use review of the section and the type of distress that may be present. Mostly FDR is used when road reconditioning is needed and there is in adequate base for the anticipated ESAL design
- Cost and minimal disruption

- Pavement condition
- Cost, reuse of existing resources
- Rural setting, few manholes in street lower cost alternative to reconstruction

County:

- Use ICON Pavement Management - no trigger for FDR.
- We use a spread sheet developed in house and do a road trip every year to determine our needs.
- MnDOT pavement ratings used to develop list of candidates. Engineering judgment used to prioritize within the list of candidates. No set condition index used
- Our pavement management system helps us identify what roads are near the end of their useful life. We use engineering judgment to determine what fix is appropriate for each road (FDR, PCC OL, Full Grading, etc.)
- We are moving towards a condition index trigger, we just have to get the right people on board, currently we are using pavement age and condition by physically driving and deciding what roads need to be in the program.
- Pavement condition
- Amount of cracking and not enough asphalt/strength for CIR
- Can't afford to reconstruct. The shame is we end up with narrower roads that still have steep inslopes.
- Top width of the existing roadway to accommodate some raise in profile due to the FDR and overlay process
- FDR is a good tool especially when shoulder width is narrow and strength can be gained from existing base
- Typical section in width, inslope and that widths would allow a 10 ton design
- Existing pavement thickness; Aggregate base thickness; Roadway width
- Cost
- Pavement condition. Pavements in fair condition would be candidates for concrete overlays or asphalt overlays. Poor pavements are FDR candidates
- Strength of roadway base

- Reestablish the homogeneous pavement structure when it is severely cracked. Help to prevent reflective cracking in failed joints
- Existing bituminous thickness
- Pavement age, traffic count

3. Do you use any "life cycle cost analysis" type of calculations in the selection process?

City:

- No official calculations. By eliminating the reflective cracking we feel the life cycle of the road will increase. There is an additional cost for the emulsion, but the thickness of asphalt required is reduced, so less asphalt is needed
- Yes, we expect to get at least 25 years out of a FDR with the correct maintenance schedule. We are only experiencing around 10 years out of a mill and overlay therefore that is taken into account when we choose the type of maintenance method
- Instead of life cycle cost we are more interested in pavement performance head to head comparisons with mill and fill projects.
- We use the ICON pavement management program and assume a 30 year life on new pavements placed on the FDR material. If we need to generate aggregate base materials, we use FDR to create the materials for use on the project.
- N/A

County:

- Not really, many of these road segments are picked because they are so bad you know you will get little life from a typical overlay
- No, just look at dates of last project done and condition of road.
- N/A

4. Do you have a procedure to select candidate roads for full depth reclamation? Please provide additional information if necessary

City:

- Those that have been edge milled and overlaid once before

- The pavement management rating system is used to determine what street segments require reclamation. Inspections of the segments are used to determine the priority of which segments are actually reclaimed

- Most of Columbia Heights has clay soils. FDR is used when pavement and aggregate base is thick enough to reclaim and subbase strength is adequate

- Roads that are over 25 years of age

- Yes, with the City of Northfield also having to take into consideration the age of the Utilities (sewer, water main) that is the main variable that is analyzed when deciding on the FDR. If we know the utilities are in good condition, and we can get a minimum of 25 more years out of a road, than a FDR is definitely considered.

- Pavement management system triggers an overlay or possibly partial reconstruction (curb and gutter is in good condition). Staff reviews the cross-section of the existing pavement and strength of the subbase to evaluate best construction method

County

- Pavement section must have adequate layer of aggregate base to blend with asphalt layers (preferably 6" min.)

- Visual & discussion

- The ones we won't be able to drive on in a couple years

- Any Road with sharp transverse cracks and or quite narrow is a possible candidate

- Roads requiring resurfacing but not expansion or reconstruction are selected for FDR

D. <u>Improvements in FDR process</u>

1. Please list the top three reasons for using FDR in urban/suburban environment

City:

- Recycles all old pavement

- Provides salvaged material
- Very stable base material
- The rehabilitated pavement is a new street. The excess class 7 can be utilized on another project as base material. Quick, limited disturbance to the residents Y
- Lower cost alternative to reconstruction
- Maintain traffic during construction
- Recycle hard aggregates into base
- Life cycle of the road is increased.
- Emulsified base becomes very hard. Great surface to drive on until the asphalt is placed.
- Equipment is not very large
- Reduces trucking cost
- Competitive costs
- Less trucking, more economical than hauling out materials and hauling virgin back, sustainability
- Eliminates reflective cracking

County:

- Should allow sustained traffic, as gravel base for extended period if needed
- Recycling
- Increased strength
- Lower cost than reconstruction
- Elimination of reflective cracking
- Cross slope correction
- Grade correction
- Increase the pavement structure without increasing the pavement height

- Reestablish the roadway crown
- Retains existing grades and slopes
- Can provide additional strength
- Retains existing grades and slopes
- Reestablish the pavement structure

2. Please list the top three reasons against using FDR in urban/suburban environment

City

- More costly than a mill and fill
- Longer construction times
- More temporary traffic control
- Constructability of FDR in an Urban setting. I would be more inclined to try it when I didn't have a location for excess reclaimed material
- Matching existing curb/gutter elevation is main reason we don't use FDR in urban environment
- Utility conflicts
- Wet or lack of aggregate base condition
- Matching elevations
- Takes more time to complete than other rehabilitation options.
- Higher initial cost
- In state aid, getting reclamation mixture to pass gradation testing can be an issue
- Does not address problems with underlying subgrade
- Cost compared to overlay

- Long term performance unknown

County

- Need to remove the material so a project where it can be utilized is needed. Additional knowledge of an FDR project in an urban setting
- Need to remove material to allow for new asphalt
- Matching existing curb/gutter elevation is main reason we don't use FDR in urban environment
- Matching curb and gutter grades
- Limitations on changing road grade
- Dust, loose gravel, potholes
- We have not done an urban FDR. With the underground work that's usually required and change road profile, the reclamation would have to be removed, stockpiled and replaced and not cost effective
- Maintaining uniformity without disturbing underground facilities
- Increased construction time
- Poor older pavements may not meet specifications and have the durability requirements
- Utility Interference
- Added cost of bituminous surface

3. What type of information would you need to help you decide when to use FDR for your roads network?

City

- Type of additive to use for a given pavement/base section, based on Soils condition, amount of pavement cracking
- Minimum overlay thickness

- We have a solid history of these methods and plan to continue our proven past practice (10 projects)
- FDR with emulsion is now the City standard for asphalt rehabilitation
- We're already convinced it's a practical approach to rehab a street
- Existing section thickness of the proposed roadway
- Deflectometer testing and test cuts – are subbase and base adequate

County

- Pavement condition, pavement thickness, type of base material
- Cost & availability of qual'd contractor (s)
- I would like more information with foamed Asphalt Cement (PG 52-34)
- Existing structure
- Life cycle costs
- Effectiveness of additives, emulsion
- 10 ton design information
- Existing pavement depth, existing aggregate depth, width & ability to tie in increased road height if milling is not an option due to pavement thickness
- Life expectancy for the pavement
- Construction time for doing the work
- We are doing fine with the information we gather locally

4. Do you have any suggestions on improvements to current FDR process, such as the construction technology and the mix design?

City

- No, but we are not using additives. Only cold in-place full depth reclamation

- Current long train equipment can only be cost effective on long straight roads exceeding 2 miles.
- For city application need shorter train process on single block areas including cul-de-sacs
- FDR with emulsion is not widely used in urban/suburban settings, so not many contractors are familiar with the process. Training sessions for contractors should be offered that specifically address FDR in an urban environment
- It would be great if they could use the reclaimed material in the asphalt pavement surface. After the road is reclaimed we have to remove the top 3-4" to make room for the asphalt surface to match the existing curb height.
- Would like information on how to use without removal of material in a curb and gutter environment (probably is no method for this).
- Ability to slice in geo grid. Geo grid is preferred over cement if budget allows. The use of cement is seen a a way to make the road more susceptible to cracking.

County

- The City of Northfield has been utilizing Pavement Reclamation since the late 1990's. It has been a cost effective way for us to maintain our road system.
- I have learned a few things in the past 15 years of doing FDR's. One thing is the importance of having a good gravel base under the roads you are building now, to set them up for FDR in the future. The most successful FDR's we have performed have been FDR's where we do not get below our existing gravel
- I like the above example. The deeper we get into the base layer the better chance of existing cracks not returning.
- I would like to see a higher "GE" value in the FDR without injection. Having a better testing procedure of what is in the actual base and check the oil content and have a better prediction of what you will get out of the ground up surface. I would also like to try an asphalt injection with a tack coat applied with a 4.5" pavement over top to see the improvement.

Appendix 1a - First survey

Survey for Full Depth Reclamation (FDR) practice

for cities and counties in Minnesota

The current survey is part of a research project sponsored by the Local Roads Research Board and Minnesota Department of Transportation. The main objective is to develop guidelines for implementing FDR as a rehabilitation alternative for city and county roads. FDR is already a mature technology for highway pavements applications. Surveying current FDR practice represents an important step in developing the necessary tools to help city and county engineers make informed decisions about the use of FDR for their road network.

Please follow the steps below to complete your survey:

- Fill out as much information as possible. Leave blank if you cannot answer some of the questions.
- Disregard any formatting issues (tables moving to the next page, etc.) while you type your information.
- Try to be as clear as possible in your answers and include any additional sources of information that may bring more clarity to your response.
- At the end, save your file as "survey-wo147-your last name.docx"

Please submit your responses via email to Dr. Mihai Marasteanu at **maras002@umn.edu**

Please submit your responses by Wednesday, February 10.

Thank you very much!!!

Table 1. Contact Information

Name	
Position	
Email	
Phone number	
County	
Any additional information	

Table 2. Experience with FDR process

How many FDR projects did you have during the last 10 years?	
For each project, provide the location and length, and the additive used (cement/ foamed asphalt/ emulsion/etc)	
What was used for the pavement surface: chip seal or asphalt overlay?	
How did you select the additive used: based on costs, contractor capabilities, past experience, etc?	
Who performed the FDR design?	

Was the top old asphalt layer milled and removed or was it used in the FDR mixture?	
Any additional information	

Table 3. FDR selection process

What are the top pavement conditions/distresses for which you would consider FDR as the top rehabilitation choice?	
Do you have a pavement management system that includes triggers for the use of FDR, such as percent and severity of surface cracking, road widening, etc?	

Please list the most important criteria for selecting FDR over other rehabilitation options.	
Do you use any “life cycle cost analysis” type of calculations in the selection process? If yes, please provide additional information.	
Do you have a procedure to select candidate roads for full depth reclamation? Please provide additional information if necessary.	
Any additional information	

Table 4. Improvements in FDR process

Please list the top three reasons <u>for using</u>, and the top three reasons <u>against using</u> FDR in urban/suburban environment.	

What type of information would you need to help you decide when to use FDR for your roads network?	
Do you have any suggestions on improvements to current FDR process, such as the construction technology and the mix design?	

Thank You!!!

Appendix 1b - Second survey

Survey for Full Depth Reclamation (FDR) practice

for cities and counties in Minnesota

The current follow-up survey is part of a research project sponsored by the Local Roads Research Board and Minnesota Department of Transportation. The main objective is to develop guidelines for implementing FDR as a rehabilitation alternative for city and county roads. FDR is already a mature technology for highway pavements applications. Surveying current FDR practice represents an important step in developing the necessary tools to help city and county engineers make informed decisions about the use of FDR for their road network.

Please follow the steps below to complete your survey:

- Fill out as much information as possible. Leave blank if you cannot answer some of the questions.
- Disregard any formatting issues (tables moving to the next page, etc.) while you type your information.
- Try to be as clear as possible in your answers and include any additional sources of information that may bring more clarity to your response.
- At the end, save your file as "FDR survey wo147-your last name.docx"

Please submit your responses via email to Dr. Mihai Marasteanu at **maras002@umn.edu**

Please submit your responses by Tuesday, March 24.

Thank you very much!!!

Table 1. Contact Information

Name	

Position	
Email	
Phone number	
City/County	
Any additional information	

Table 2. Experience with FDR process

For each FDR project you had in the last 10 years, provide the year of completion, the project length, the additive used (cement/ foamed asphalt/ emulsion/calcium chloride/ fly ash/ etc.) and any additional comments	Year	Length	Additive	Any additional comments
What tests were used to assess the structural condition of the base under the FDR layers?				
Who performed the FDR pavement design? Name the pavement design method (or computer program) used.				
Who performed the material mix design for the FDR? If an additive was used, how was the specific additive selected?				

How did you check that the FDR material placed on the road matched the properties of the material tested in the lab? In other words, do you have a quality control process for FDR projects?	

Do you have a pavement management system or a procedure to select candidate roads for full depth reclamation? Do you use a condition index to trigger FDR?	
Do you use any "life cycle cost analysis" type of calculations in the selection process? If yes, please provide additional information.	
What changes/improvements would you like to see in FDR (disregard the cost factor) that would make it a more	

appealing rehabilitation method for your roads? (*Please see next page for some potential ideas*)	
Any additional information	

Potential improvement ideas

- Use a cold <u>in plant</u> recycling approach rather than cold <u>in place</u> recycling, which provides much better control of the FDR materials placed in the road. This method would require a portable plant in a nearby location and transport to and from the plant to the construction site.
- The above approach would make possible using the entire asphalt layer in FDR and removing the worst aggregate component of the base instead. This could significantly improve the performance of the FDR layer.

APPENDIX B
ADDITIONAL DATA

Creep Stiffness

Figure 21, Figure 22, Figure 23 and Figure 24 present creep stiffness curves for individual samples.

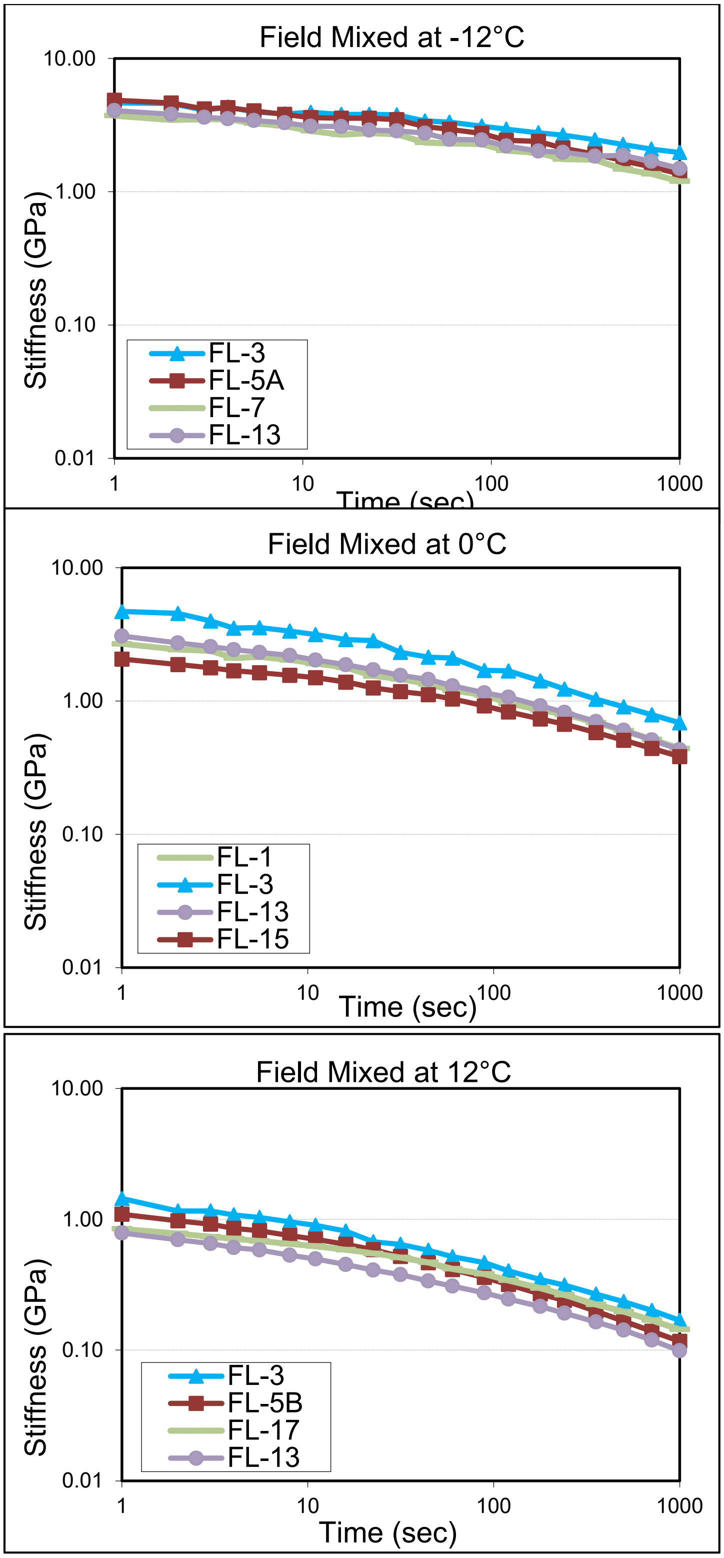
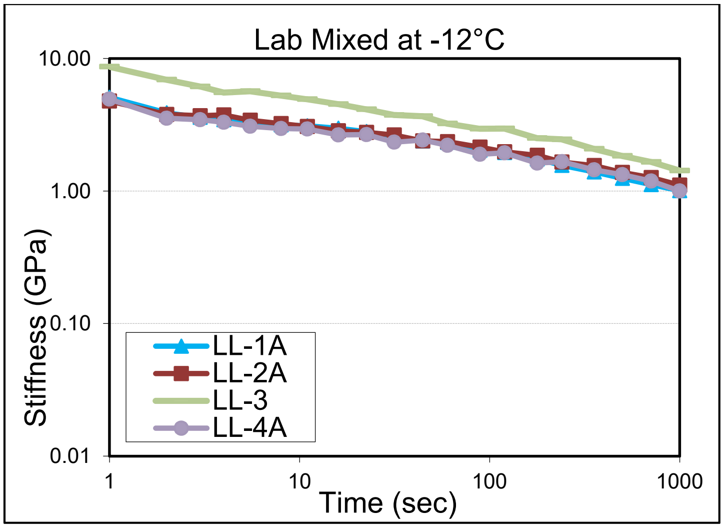
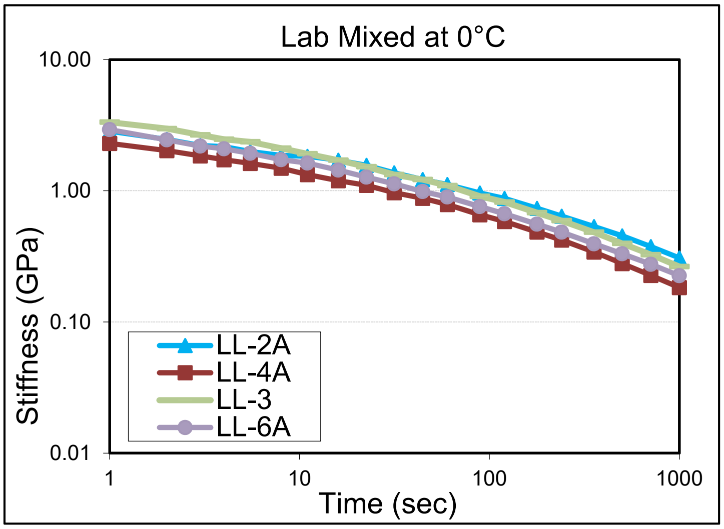


Figure 21: Creep stiffness curves for field mixed samples, at -12°C, 0°C and 12°C





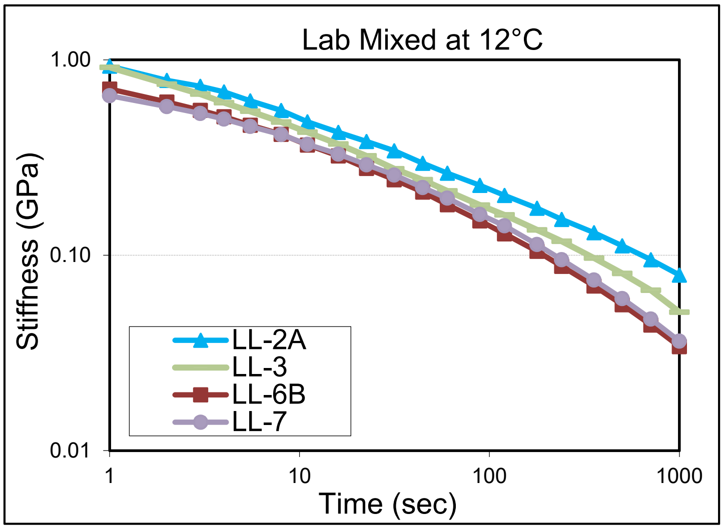


Figure 22: Creep stiffness curves for lab mixed samples, at -12 °C, 0 °C and 12 °C

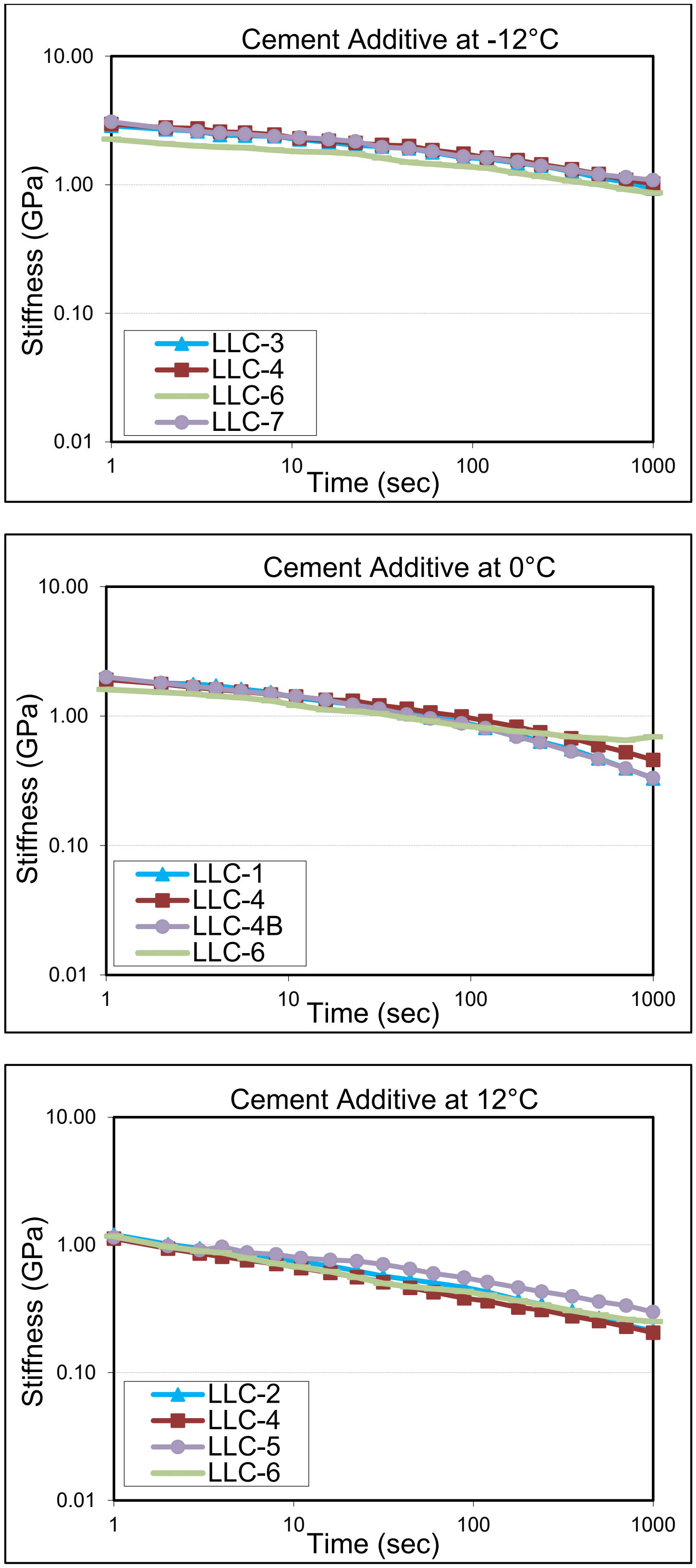


Figure 23: Creep stiffness curves for cement additive samples, at -12°C, 0°C and 12°C

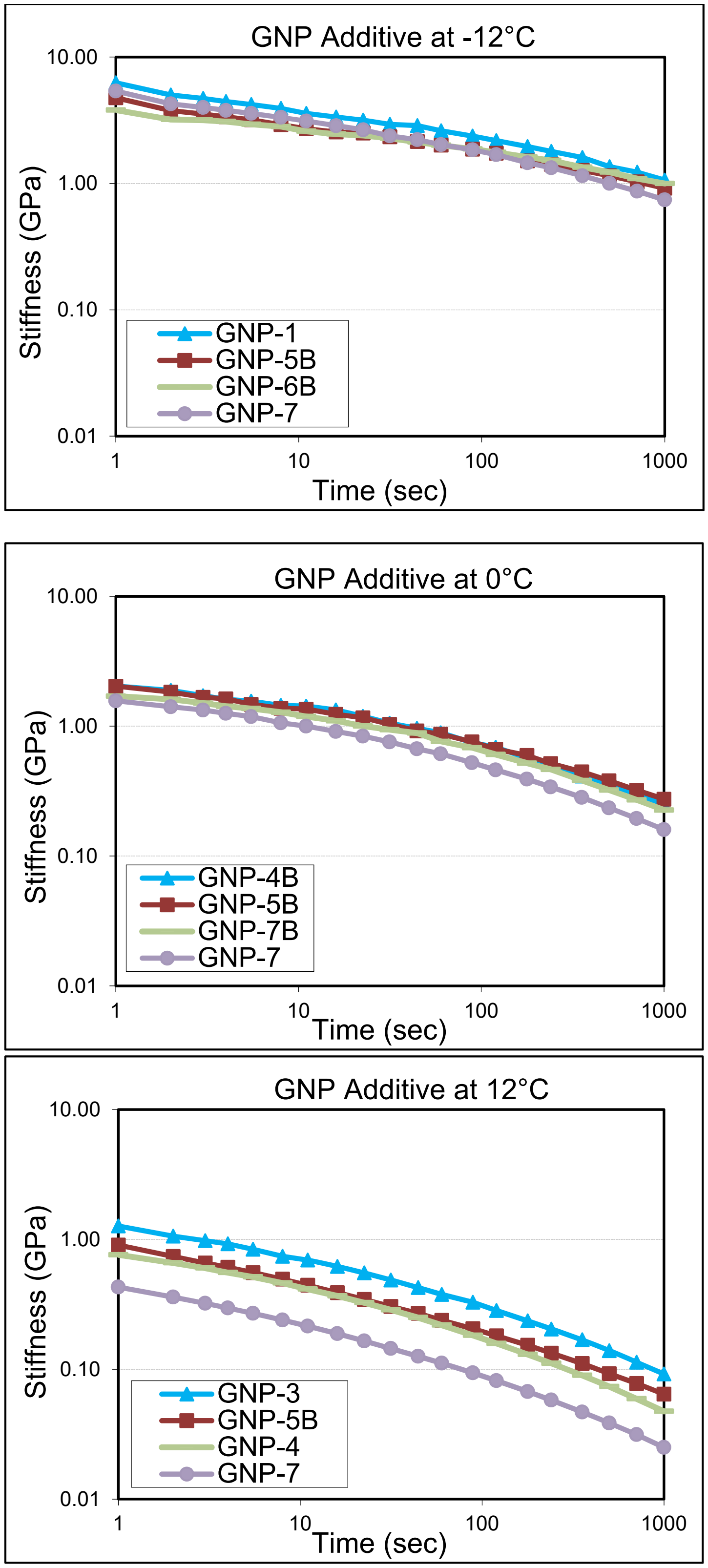


Figure 24: Creep stiffness curves for GNP additive samples, at -12°C, 0°C and 12°C

Dynamic Modulus

Figure 25, Figure 26 and Figure 27 present dynamic modulus master curves for individual samples.

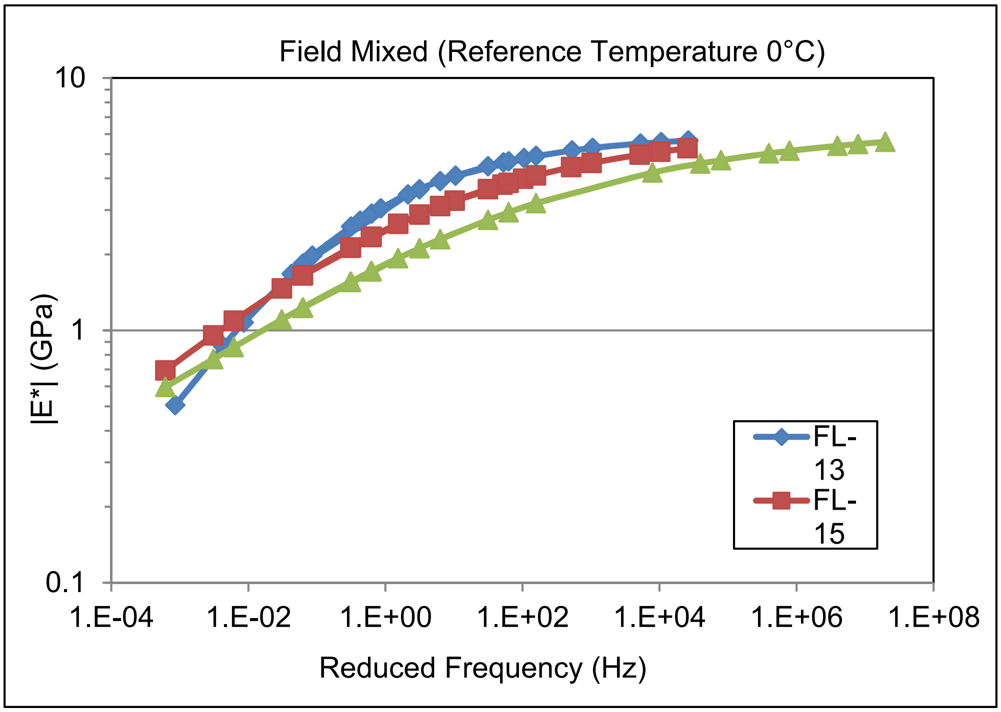


Figure 25: Dynamic modulus master curves for field mixed samples.

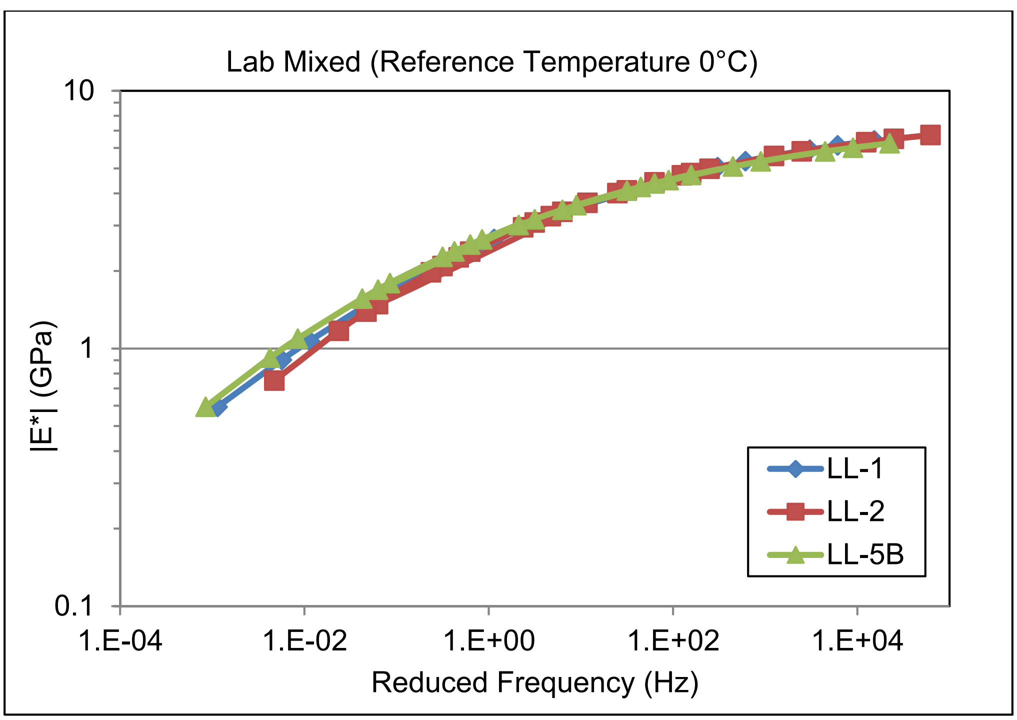


Figure 26: Dynamic modulus master curves for lab mixed samples.

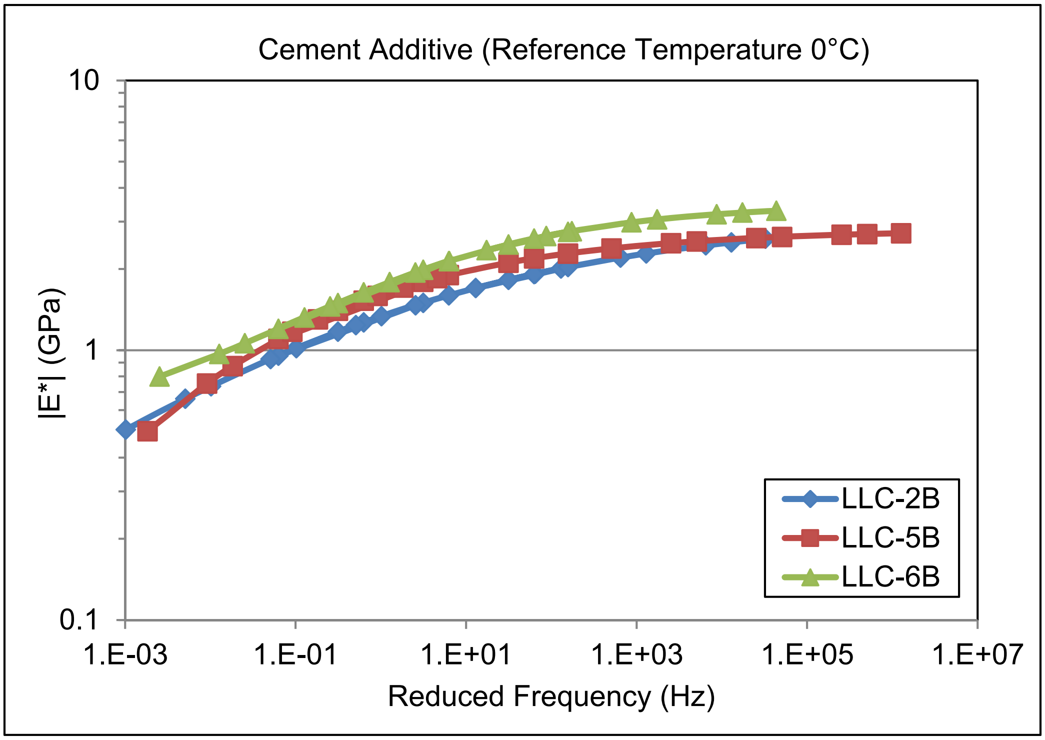


Figure 27: Dynamic modulus master curves for cement additive samples.

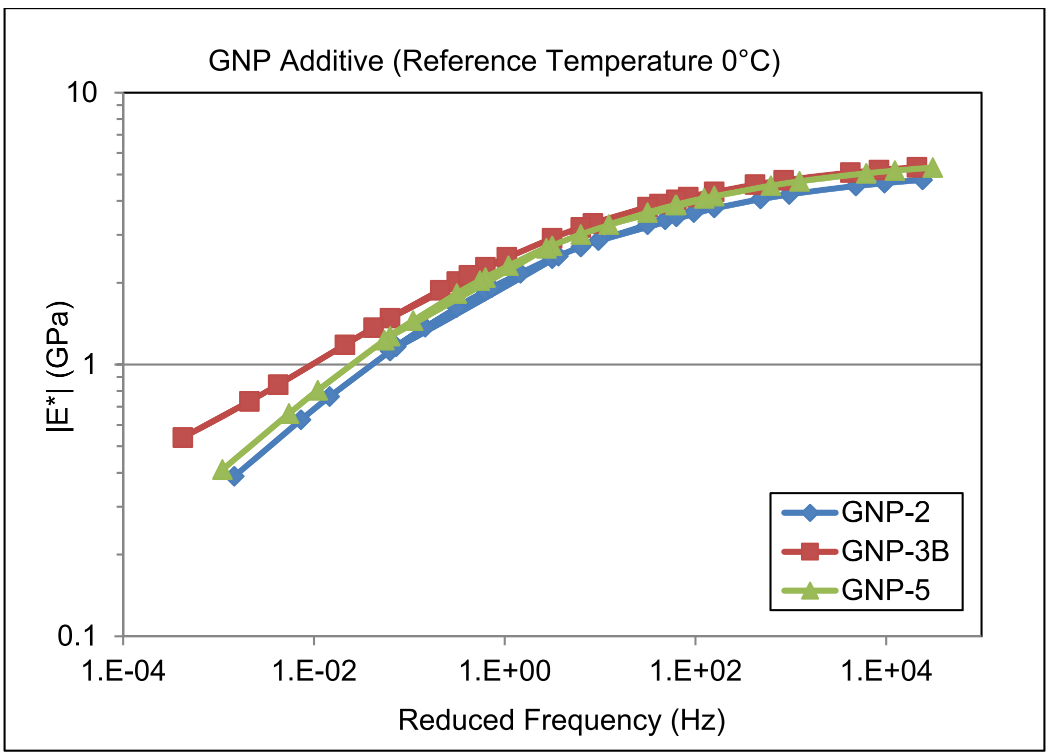


Figure 28: Dynamic modulus master curves for GNP additive samples.