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**AN INVESTIGATION ON THE MARSHALL AND RESILIENT
CHARACTERISTICS OF ASPHALT CONCRETE WITH BITUMINOUS
BINDER MODIFIED WITH HIGH DENSITY POLYETHYLENE**

PHILOSOPHY OF DOCTORATE THESIS

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**YÜKSEK YOĞUNLUKLU POLİETİLEN İLE MODİFİYE EDİLMİŞ BİTÜM
BAĞLAYICILI ASFALT BETONUNUN MARSHALL VE RESILIENT
KARAKTERİSTİKLERİ ÜZERİNE BİR İNCELEME**

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NOMENCLATURE

HDP	: High Density Polyethylene
T	: Temperature
k	: A coefficient pertaining to the binder
η_0	: Viscosity at $T = 0^\circ\text{C}$
P	: Penetration of binder at given temperature
η	: Viscosity of binder at given temperature
h	: A coefficient depending on the hardness
P_0	: Penetration at $T = 0^\circ\text{C}$
σ_v	: Derivative of Viscosity
σ_p	: Derivative of penetration
SAMI	: Stress-Absorbing Membrane Interlayer
HMA	: Hot Mix Asphalt
M_R	: Resilient Modulus
σ	: Applied stress
ϵ	: Recoverable strain
σ_x	: The tension stress
σ_y	: The compression stress
P	: Total applied load
t	: Specimen thickness
d	: Specimen diameter

x, y : Coordinate values from center of specimen

AC : Asphalt Concrete

a_i : Layer coefficient

PE : Polyethylene

PVC : Polyvinilclorür

ΔH : Horizontal deformation

μ : Poisson's ratio

LDPE : Low Density Polyethylene

S_g : Calculated Specific Gravity

P_{wi} : Percentage weight of components

S_{gi} : Specific Gravity of Components

SBS : The Styrene-rubber block copolymers

EVA : Ethylene vinyl acetate

ANOVA: Analyses of Variance

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SUMMARY

Of the principal deteriorations encountered most in the flexible pavements, the permanent deformations constitute a major problem in regard both the traffic safety and cost of repair. In order to remedy these adverse effects, it is essential that both the mix design proportions be revised and the quality of the ingredients of the mix (the aggregates and the bituminous binder) be increased. Although it is possible to use aggregates with lower wearing ratios, their availability is restricted by limited geologic formations to several rock types (basalt and granit). This restriction has drawn the attention of researchers to the second element of the asphalt mix, the bituminous binder and hence the idea of modified asphalt was born.

The purpose of this study is to investigate the influence of the High Density Polyethylene (HDP) ,as a bitumen modifier, on the Marshall and Resilient characteristics of the modified asphalt concrete. The goal of asphalt modification is to develop mix design proportions which improve the performance of the pavement by decreasing the permanent deformations.

Chapter 1 diagnoses that increasing heavy traffic loads and harsh climate conditions causes serious and unexpected early deterioration in road pavements. The components of the asphalt concrete with the HDP modified binder are explained in Chapter 2. The resilient modulus of asphalt concrete is defined in Chapter 3 where it is emphasized that the resilient modulus has gained popularity as a means of evaluating the response of asphalt concrete to loads. In this study the resilient modulus has been determined by the diametrial resilient modulus test which is a nondestructive test and allows the testing of the specimen under different conditions to avoid specimen-to-specimen variations. In Chapter 4, a survey of past studies on the polymer modified asphalt concrete are given. Materials and Procedures are presented in Chapter 5 where the results of investigation on the effects of mixing temperature (145-155-165°C), mixing time (5-15-30 min.) and HDP content (0-2-4-6-8) on the rheologic properties of the binder are presented. During the research, a plethora of Marshall and Resilient Modulus tests have been performed on the Marshall specimens and the effects of mixing time, mixing temperature and HDP content on the Marshall and Resilient characteristics have been determined. The Resilient Modulus tests have been performed at four test temperatures (5-25-40-60°C) , each repeated for three different rise time values (30-60-100ms).

As a result, for a given mixing time and mixing temperature, while penetration and ductility decrease, viscosity and softening point increase proportionally with increasing HDP content. Marshall stability increases up to 4% HDP and decreases there on. The resilient modulus displays a similar trend. Mathematical models have been established for each resilient modulus test. Statistical evaluations has revealed good correlation between observed and predicted values.

ÖZET

Ağır ticari trafik hacminin artması ve iklim koşullarının bozucu olumsuz etkileri, esnek üstyapı kaplamalarında ondülasyon, tekerlek izi ve yığılma gibi kalıcı deformasyonlar oluşmasına sebep olmaktadır. Bu tür sorunlara en uygun çözüm, esnek üstyapının performansının artırılmasıdır.

Bu amaçla son yıllarda bitümlü bağlayıcılar değişik katkı maddeleri ile modifiye edilmekte ve elde edilen bağlayıcı ile hazırlanan asfalt betonu karışımlarının yol üstyapı performansını artırdığı görülmektedir. Modifiye edilmiş bitümlü bağlayıcılar, asfalt betonu karışımlarının rijitliğini artırarak yüksek sıcaklıklardaki kalıcı deformasyonları azaltmak ve yol üstyapısının yorulma ömrünü artırmak gibi sebeplerle kullanılmaktadır.

Bu çalışmada Yüksek Yoğunluklu Polietilen (HDP) ile modifiye edilmiş bitümlü bağlayıcıların asfalt betonu karışımlarının Marshall Stabilesi ve Elastisite Modülü üzerindeki etkileri incelenmiştir.

Bu amaçla yapılan çalışma 7 bölüm halinde sunulmuştur.

Giriş bölümü olan birinci bölümde, bir yol üstyapısının, proje ömrü boyunca üzerine gelen trafik yükünü büyük bozulmalara ve çatlamalara maruz kalmadan taşıyabilmesi ve yükü taban zemininin taşıyabileceği düzeye düşürerek tabana iletmesi gerektiği, ayrıca ağır trafik hacmi ile lastik iç basınçları ve dingil yüklerinin artışından dolayı yol üstyapı performansında azalmalar olduğundan, performansın artırılması için bitümlü bağlayıcıların çeşitli katkı maddeleri ile modifiye edilmesi gerekliliği belirtilmiştir. Aynı bölümde modifiye edilmiş malzemenin visko-elastik ve reolojik özelliklerine ait yeni laboratuvar deneylerinin yapılması, asfaltın kimyasal yapısının katkı maddeleri ile uygunluğunun incelenmesi ve hizmet esnasındaki davranış değişikliğinin saptanması gerekliliği vurgulanmıştır. Son olarak bir yol üstyapısında modifiye asfalt kullanılmasını gerektiren sebeplerin,

- Bitümlü karışımların rijitliğini artırarak yüksek sıcaklıklardaki kalıcı deformasyonları azaltmak,
- Yol üstyapısının yorulma ömrünü artırmak,
- Bağlayıcının sıcaklığa karşı duyarlılığını azaltmak, bitümlü karışımın yüksek sıcaklıklardaki viskozite kaybını düşürmek ve bağlayıcı kusmasını (bleeding) önlemek,
- Düşük sıcaklıklarda (kış şartları) oluşan termal çatlakları azaltmak,
- Nem durumunda soyulmayı önlemek için bağlayıcı ve agrega arasındaki adhezyonu artırmak,
- Bakım masraflarını azaltmak,
- Daha iyi bir sürüş yüzeyi oluşturmak,
- Tabakanın çatlamış bir üstyapı üzerine serilmesi halinde yansıma çatlaklarını önlemek

şeklinde sıralanabileceği vurgulanmıştır.

Modifiye edilmiş asfalt betonlarında kullanılan bileşenler adlı ikinci bölüm asfalt betonunu oluşturan ana bileşenler(bitümlü bağlayıcı, agrega, polimerler) ve bu bileşenlerin özellikleri ile ilgilidir. Bitümlü bağlayıcının asfalt betonundaki rolünün agrega danelerini sarıp boşlukları doldurarak agregaları birbirine bağlamak olduğu ve yol üstyapı performansına etkisinin de visko-elastik davranış şeklinde kendini gösterdiği belirtilmiştir. Bitümlü bağlayıcının özellikleri olan penetrasyon, viskozite, duktilite, yumuşama noktası, kırılma noktası ve sıcaklığa karşı duyarlılık gibi kavramlar açıklanmıştır.

Yıllardır araştırmacıların ve kimyagerlerin endüstri amaçlı kullanımlar için bitüme asbest, filler, mineral filler ve kauçuk gibi maddeler karıştırarak modifiye edilmiş bitümleri denedikleri, son 20 yıldır ise bir çok araştırmacının, yol inşasında kullanılan bitümler için çok sayıda katkı malzemesi araştırdıkları yine bu bölümde belirtilmiştir.

Bir katkı malzemesi etkili, pratik ve ekonomik kullanımı için aşağıdaki karakteristiklere sahip olmalıdır;

- kolay elde edilebilmeli
- asfalt karıştırma sıcaklıklarında gradasyonun bozulmasına (degradation) karşı dirençli olmalı
- bitümle kolay karışabilmeli
- yüksek sıcaklıklarda, karıştırma ve serme sıcaklıklarında bitümü aşırı derecede viskoz yapmadan, düşük sıcaklıklarda ise fazla rijit ve gevrek yapmadan akmaya karşı direnci geliştirmeli
- ekonomik olmalı

Penetrasyonun asfalt çimentolarının kıvam durumlarının bir ölçüsü ve sıcaklığın üssel(artan) bir fonksiyonu olduğu, viskozitenin ise bir bağlayıcının akışkanlığının bir ölçüsü olduğu ve viskozitenin de sıcaklığın üssel(azalan) bir fonksiyonu olduğu, duktilitenin, yavaş etkiyen yükler altında bağlayıcının uzama kabiliyetinin bir ölçüsü olduğu ve viskozite ile çekme direnci arasında geçiş teşkil eden bir özellik olduğu, penetrasyon artınca veya viskozite azalınca duktilitenin arttığı ifade edilmiştir.

Çok sert bağlayıcılar için penetrasyonun sıfıra eşit olabileceği, bu tür bağlayıcıların kıvam durumlarının yumuşama noktası deneyi ile saptandığı belirtilmiştir. Ayrıca asfaltın sıcaklığa karşı duyarlılığının penetrasyon veya viskozitenin zamana göre türevleri(zamana göre değişimleri) olduğu, kırılma noktasının da asfalt çimentosunun düşük sıcaklıklardaki davranışını belirttiği ve Fraass metodu ile ölçüldüğü açıklanmıştır. Aynı bölümde polimerlerin, polimerizasyon olarak bilinen bir kimyasal işlem ile birbirine bağlanan monomerlerin tekrarlı bağlarından oluşan bir malzeme olduğu, bir çok malzemenin polimer olarak adlandırılabilmesi ve bunlara doğal kauçuk, sentetik kauçuk, polipropilen, polietilen ve polivinilklorür'ün örnek olarak verilebileceği belirtilmiştir. Ayrıca polimerlerin elastomer ve plastomer olmak üzere 2'ye ayrıldığı, çalışmada kullanılan polimerin yüksek yoğunluklu polietilenin(HDP) bir plastomer olduğu açıklanmıştır.

Yine bu bölümde HDP'nin bir katkı maddesi olarak diğer polimerlerden farklı bir davranış sergilediği, polietilen dışındaki diğer polimerlerin hepsinin asfalt çimentosu içinde homojen olarak erirken polietilenin asfalt çimentosu içinde erimediği fakat mikron boyutundaki danelerin(partiküllerin) üniform bir şekilde dağıldığı, HDP' nin asfalt çimentosu bileşenlerinden daha büyük moleküler ağırlığa sahip olduğu vurgulanmış, uzun zincirli geniş polietilen kristallerinin asfalt çimentosunun düşük moleküler kütlelerinde takviye oluşturduğu ve bu yolla asfalt çimentosunun reolojik özelliklerini geliştirdiği, aynı zamanda polietilen moleküllerinin uzun ve esnek zincirlerinin mineral agreganın yüzeyine sıkı bir şekilde tutunarak, agrega ve bağlayıcı arasındaki adhezyonu artırdığı belirtilmiştir.

Resilient modülün(M_R) elastik modülden farklı bir kavram olduğu, yükleme hızı ve sıcaklığa bağlı olarak değiştiği, asfalt betonunun visko-elastik davranışından dolayı, asfalt betonların davranışlarının resilient modül ile karakterize edildiği 'Asfalt Betonlarının Resilient Modülleri' adlı 3.bölümde açıklanmıştır.

Asfalt betonlarının resilient modüllerinin ASTM D 4123-82 de detaylı bir şekilde anlatılan indirekt Çekme Deneyi (Indirect Tensile Test) ile belirlendiği, resilient modülü hesaplanırken yükün numuneye uygulanma şekli ve yük ile numunede oluşan yatay ve düşey deformasyonların Timoshenko' nun elastik bir diskteki gerilme analizine göre yapıldığı, bu deneyin diğer modül belirleme deneylerine olan üstünlükleri açıklanmış ve Marshall numuneleri üzerine uygulanan, bu deneyde kullanılan yükleme sürelerinin düşük olduğu, deney elastik bölgede yapıldığı için numunenin deney esnasında hasara uğramadığı ve bir numune üzerinde değişik sıcaklık ve yükleme koşullarında bir kaç kez deney yapılabileceği belirtilmiştir. Bu bölümün sonunda AASHTO 86 esnek üstyapı tasarım rehberinde önerilen, resilient modül ile aşınma tabaka katsayısı ilişkisi açıklanmış ve bu ilişkiden tabaka katsayısının resilient modül' ün artması ile arttığı fakat 450.000 psi resilient modül değerinden sonraki değerlerde termal ve yorulma çatlakları oluşabileceğinin dikkate alınması gerektiği vurgulanmıştır.

'Polimer ile Modifiye Edilmiş Bitümlü Bağlayıcı Hazırlanan Asfalt Betonları Üzerinde Yapılmış Çalışmalar' adlı dördüncü bölümde, polimer ile modifiye edilmiş bitümlü asfalt betonlar üzerinde yapılan çalışmalar verilmiştir. Bitümlü bağlayıcıya polimer katılmasının penetrasyon ve viskozite sonuçlarına bakılarak bağlayıcının sıcaklığa duyarlılığını azalttığı, latex'in bitümlü bağlayıcı ile agrega karıştırılmadan önce bitümlü bağlayıcı ile karıştırılmasının, agrega ile bitümlü bağlayıcının karıştırılması sırasında katılmasından daha fazla bir yorulma ömrü kazandırdığı belirtilmiştir.

Asfalt'a neoprene katılmasının, yumuşama noktasını artırıp penetrasyonu azaltarak asfaltın sertliğini artırdığını, yaşlanma özelliklerini iyileştirdiği, polimerize edilmiş asfalt karışımının özelliklerinin polimer tipine ve asfaltın kaynağına bağlı olduğu açıklanmıştır. Yine bu bölümde, önceleri asfalt'a % 7.5 ve % 10 oranlarında polimer katılmasının önerildiği fakat daha sonra asfalt ağırlığının % 3'ünden fazla miktarların yola uygulamada zorluklar çıkardığı ve bu nedenle % 3 oranının tercih edildiği vurgulanmıştır.

Styrene-butadiene-styrene (SBS) polimerinin bağlayıcının sıcaklığa karşı duyarlılığını azalttığı, kohezyonu, agrega ile adhezyonu ve esnekliği artırdığı açıklanmıştır. Yine bu bölümde, USA' da ve deniz aşırı ülkelerde yapılan çeşitli yol uygulamalarının, polimer ile modifiye edilmiş bağlayıcıların üstyapı hizmet ömrünü artırdığı ve maliyeti azaltıcı etkisinin görüldüğü, polimer modifikasyonunun, üstyapının tekerlek izi oluşumuna karşı direncini artırdığı belirtilmiştir.

Latex' in kullanımı Greeg tarafından araştırılmıştır. Latex, doğal kauçuk kullanarak SBR den yapılmış bir üründür. Greeg, bitüme polimer katılmasının, viskozite ve penetrasyon ile de belirlendiği gibi sıcaklığa karşı duyarlılığını azaltmıştır.

Lewis ve Wellborn, polimerize edilmiş asfalt karışımın karakteristiklerinin polimerin tipine(yani doğal, sentetik veya volkanize olup olmamasına) ve asfaltın yapısına ve kaynağına bağlı olduğunu vurgulamışlardır.

Polimerize edilmiş asfalt kaplama karışımının hazırlanmasında karşılaşılan problemlerden biri de, polimerin bitümlü bağlayıcı içinde dağılmasıdır. Bu problemi çözmek için çok sayıda farklı yaklaşımda bulunulmuştur. Bunlardan birkaçı, polimeri bitümlü bağlayıcıya toz veya sıvı halde karıştırmanın, asfalt bağlayıcı ile polimeri önceden karıştırmak veya karışım yola serilip sıkıştırıldıktan sonra, üstyapının polimerize edilmesi ile çözülebileceğini savunmuşlardır. Önceleri kauçuk olarak biline polimer başlıca bakım ve onarım işlerinde kullanılmıştır. Literatür incelendiğinde görülecektir ki; araştırmacılar, bağlayıcıya polimer ilavesinin yüksek sıcaklıklarda bağlayıcının elastik davranışını ve karışımın adhezyonunu artırdığı ve bağlayıcının sıcaklığa karşı duyarlılığını azalttığı konusunda aynı düşüncededirler.

Son yıllarda, üstyapılar önemli miktarda artan kamyon trafiği, lastik basıncı ve dingil yüklerine maruz kalmıştır. Geçmişte geleneksel sıcak karışım asfalt dizaynı iyi performans gösterirken, ağır yüklere maruz kalan asfalt kaplamaların erken tekerlek izi oluşumunu azaltmak için yeni yaklaşımlara ihtiyaç vardır.

Sıcak karışımlarda bağlayıcı olarak kullanılan bitümlü bağlayıcının, farklı oranlarda(% 0-2-4-6-8) Yüksek Yoğunluklu Polietilen (HDP) ile değişik karıştırma sıcaklıkları* (145-155-165°C) ve karıştırma sürelerinde** (5-15-30 dakika) karıştırılarak, karıştırma sıcaklık ve süreleri ile HDP oranlarının, modifiye edilmiş bağlayıcıların reolojik özellikler üzerindeki etkisi tezin amacı doğrultusunda 'Deneysel Çalışma' adlı beşinci bölümde incelenmiştir.

Araştırmada hazırlanan numuneler ve bu numuneler üzerinde gerçekleştirilen deney sayıları aşağıdaki gibidir :

Optimum bitümlü bağlayıcı yüzdesini bulmak için % 2.5 – 3 – 3.5 – 4 – 4.5 – 5 – 5.5 – 6 – 6.5 – 7 oranları için 3'er numune(toplam 30 numune),

Optimum bağlayıcı oranını kullanarak % 0-2-4-6-8 oranlarında Yüksek Yoğunluklu Polietilen (HDP) ile modifiye edilmiş bağlayıcılar ile Marshall deneyleri için hazırlanan numune sayısı:

Bitümlü bağlayıcı ile HDP Karıştırma süresi : 3 (5-15 ve 30 dakika)

Bitümlü bağlayıcı ile HDP Karıştırma sıcaklığı : 3 (145-155-165°C)

Her bir karışım için hazırlanan numune sayısı :3

Yüksek Yoğunluklu Polietilen Oranı : 4 (%2-4-6 ve 8)

$3*3*3*4 = 108$ numune

Polietilensiz bağlayıcı 3 adet numune

Marshall deneyleri için toplam 141(30+108+3) adet Marshall numunesi hazırlanmıştır

Resilient Modül için de 108 adet polietilenli 3 adet polietilensiz numune olmak üzere toplam 111 adet Marshall numunesi boyutlarında numune hazırlanmıştır.

Marshall deneyleri ve Resilient Modül deneyleri için toplam 252 adet numune hazırlanmıştır.

Resilient Modül için hazırlanan 111 adet numune üzerinde 4 deney sıcaklığı (5-25-40 ve 60°C) ve 3 yük çıkış süresi(30-60 ve 100ms) için her bir numunenin birbirine dik 2 noktadan Resilient Modül deneylerinin yapıldığı da göz önüne alınırsa toplam resilient modül deney sayısı,

$4*3*2*111 = 2664$ deney yapılmıştır.

Bu bölümde ilk olarak karıştırma süresi, karıştırma sıcaklığı ve HDP oranının modifiye edilmiş bitümlü bağlayıcının reolojik özellikleri üzerindeki etkileri incelenmiş, modifiye edilmiş bağlayıcılar ile hazırlanan beton asfalt numuneler üzerinde yapılan Marshall stabilize deneylerinde, karıştırma sıcaklık ve karıştırma süreleri ile HDP oranlarının Marshall stabilitesi, Marshall akması, boşluk oranı, bağlayıcı ile dolu agrega boşluğu oranı ve birim ağırlık değerleri üzerindeki etkilerinin gözlemlendiği belirtilmiştir. Ayrıca Bitümlü Kaplamalar Fenni şartnamesinde aşınma tabakası için verilen ölçütler göz önüne alınarak, maksimum stabiliteyi veren karıştırma sıcaklığı, karıştırma süresi ve HDP oranının belirlendiği açıklanmıştır.

AASHTO 86 esnek üstyapı tasarım rehberinde aşınma tabakası için son derece önemli olan resilient modül deneyinin Marshall numuneleri üzerinde yapıldığını ve resilient modül üzerinde, resilient modül deney sıcaklıklarının (5-25-40 ve 60°C), değişik yük çıkış sürelerinin(rise time 30-60-100 ms), HDP oranlarının (%0-2-4-6 ve 8), karıştırma sıcaklıklarının(145-155-165°C) ve karıştırma sürelerinin(5-15-30 dakika) resilient modül üzerindeki etkilerinin araştırıldığı açıklanmıştır.

‘HDP ile modifiye edilmiş asfalt betonlarının resilient modülleri için matematik model kurulması’ adlı altıncı bölümde deney verilerine bağlı olarak ampirik bir matematik model kurmanın temel prensipleri açıklanmıştır. Tek değişkenin etki ettiği bir fiziksel olayın, birden fazla değişkene bağlı olarak açıklanabilen olaylara oranla daha kolay modellenebileceği, ayrıca çok değişkene bağlı olayların doğrusal olmayan bir denklem takımı ile modellenmesi durumunda izlenmesi gereken prosedür açıklanmıştır. Kurulan modellerin deney esnasında ölçülen geri dönen deformasyon miktarını tahmine yönelik olduğu, geri dönen deformasyona etki eden bağımsız değişkenler arasında öncelikli olarak bir korelasyon matrisi kurularak, bağımsız değişkenlerin birbirleri ile ilişkileri incelenmiş ve bütün değişkenlerin birbirinden bağımsız olarak ayrı ayrı geri dönen deformasyonu etkilediği görülmüştür. Yük çıkış süresi (rise time), karıştırma

CHAPTER 1

INTRODUCTION

Throughout its project life, a road pavement is expected to carry the traffic load without showing severe deteriorations (deformations) and cracking and reduce on the surface stresses to a level so as to be carried by the subgrade. Large variations in the climate and the ever increasing heavy traffic volume cause adverse effects on the performance of a pavement.

For this reason, construction of highways capable of resisting severe exterior attacks has gained importance and hence the improvement of pavement performance. Of the principal deteriorations encountered in flexible road pavements, the plastic deformations (ondulation, rutting ..etc.) constitute serious problems with regard both to safety and cost of maintenance. In order to solve these problems, both the asphalt mix proportions should be revised and the quality of the constituents of the mix, i.e. the aggregate and the bituminous binder, should be increased. Though increasing the quality of the aggregates is somewhat possible, the application is limited to several rock types which have higher resistance to polishing (basalt, granite). Moreover, this effort is further restricted by the scarcity of proper geologic formations.

The limited availability of higher quality aggregates has drawn the attention of the researchers to the other component of the asphalt mix, the binder hence the idea of modified asphalt was born. Because the visco-elastic behaviour of the bituminous binder plays a crucial role in the performance of the highway pavements, bitumen modification has been the subject of most of the recent studies. In many institutions world-wide, research studies on asphalt modification are being continued, and the properties of the bitumens modified by various additives in various proportions are being investigated.

Because the subject- matter of modified asphalt is new, it is essential that the visco-elastic and rheological properties of the modified binder be determined by laboratory experiments and the consistency of the modifier with the chemical composition of the asphalt be verified, as well as the alterations in the behaviour of the material during storage, application and service conditions be investigated. In Turkey, increasing traffic loads and harsh climate conditions have been causing serious and unexpected early deteriorations in road pavements. This situation emphasises the importance of realisation of high performance pavements.

The purpose of this study is to investigate the potential advantages of use of the binder modified by high density polyethylene in asphalt pavement in reducing permanent deformations encountered especially in hot climate areas.

The following are the motives to use modified asphalt in highway pavements;

- to reduce permanent deformations observed at high temperatures by increasing the rigidity of the bituminous mix.
- to extend the fatigue life.
- to reduce the sensitivity of the binder to temperature effects, to mitigate the loss of binder viscosity at high temperatures and to prevent binder bleeding.
- to mitigate thermal cracks at low temperatures (winter conditions).
- to reduce maintenance costs.
- to obtain an improved riding surface.
- to prevent stripping due to present moisture by increasing adhesion between the binder and the aggregate.
- to prevent reflection cracks when the bituminous cover has been laid out on previously cracked pavement.

CHAPTER 2

THE COMPONENTS USED IN THE ASPHALT CONCRETE WITH THE HDP MODIFIED BINDER

2.1 INTRODUCTION

Asphalt concrete consists of binder and well - graded aggregate. The binder may be normal penetration grade bitumen or a modified bitumen. In this investigation the modifier used consists of High Density Polyethylene particles.

2.2 BITUMEN AS A ROAD MATERIAL

Asphalt cement, either softened or unsoftened, is a specially prepared petrol asphalt which provides a certain consistency and quality so as to be used in the manufacture of bituminous mixtures. Asphalt, composed mainly of bitumen, can be found naturally or obtained from crude oil or by mixing bitumens from different sources. It is thick in consistency (solid to semi-solid) and when heated softens gradually. Its colour ranges from black to dark brown.

Bitumen, a mixture of natural or proven hydrocarbons or both, is a highly viscous solid or liquid which dissolves completely in carbon disulfide.

Regardless of their quality of construction, almost all asphalt pavements display cracking after 2-3 years of service. Yet, if the deformations an asphalt pavement experiences under the loads, which the pavement it is likely to be subjected to throughout its life, can be calculated and necessary measures are taken to reduce them, then it will be possible to extend the service life of a pavement. To this end, it

is essential first to understand the behaviour of an asphalt pavement under various loading conditions.

Rheology provides a means to evaluate this behaviour, as it investigates the deformations considering both the load and its time variation. In this connection, asphalt has been regarded as a rheologic material. However, because its resistance and hardness varies with temperature asphalt is also a thermoplastic material.

2.2.1 Viscosity

Viscosity is a fundamental characteristic of a bitumen, as it determines how the material behaves at a given temperature and over a temperature range. Viscosity is a measure of liquidity of the binder. It is related to the temperature with the following equation :

$$\eta = \eta_0 e^{-kt} \quad (2.1)$$

where,

T : temperature

k : a coefficient pertaining to the binder

η_0 : viscosity at T = 0°C

The true value of viscosity is not used, instead a viscosity level in terms of seconds which is determined from a flow experiment is generally referred. Viscosity grading of asphalt cements are normally based on viscosity values at 60°C. Also the viscosity at 135°C is usually specified and referred to as the nominal minimum viscosity. The purpose is to describe limiting values of consistency at these two temperatures. The 60°C temperature was chosen as it approximates the maximum temperature of asphalt pavement surfaces in service in the United States and elsewhere in the world where substantial road building activity is in progress. The 135°C temperature was chosen as one that approximates mixing and laydown temperatures for hot mixes [1].

Carre and Laurent[2] have given the relationship between penetration and viscosity for the bitumen used in road construction at given temperature. These equations for the bitumen above 60 penetration are ,

$$\log P = -0.465 \times \log \eta + 4.275 \quad (2.2)$$

or

$$P = 5.305 \times 10^4 \times \eta^{-0.4651} \quad (2.3)$$

for the bitumen below 60 penetration :

$$\log P = -0.385 \times \log \eta + 4.228 \quad (2.4)$$

or

$$P = 1.69 \times 10^4 \times \eta^{-0.385} \quad (2.5)$$

in terms of viscosity as the function of penetration for the bitumen above 60 penetration :

$$\eta = 1.45 \times 10^{10} \times P^{-2.15} \quad (2.6)$$

for the bitumen below 60 penetration

$$\eta = 9.50 \times 10^{10} \times P^{-2.60} \quad (2.7)$$

where,

P = penetration of binder at given temperature

η = viscosity of binder at given temperature

2.2.2 Penetration

The penetration is the normal criterion of consistency and has a wide measuring range. Also the value of penetration is an indication of the resistance to deformation and closely related to viscosity.

The flow experiments are suitable only for thin binders which flow relatively fast. For thicker binders, viscosity is determined from penetration tests. A standard needle penetrates the sample vertically under known conditions of loading time and temperature. Similar to viscosity, penetration depends on temperature exponentially. But, unlike viscosity, penetration increases with temperature. The relationship can be expressed with the following :

$$P = P_0 e^{hT} \quad (2.8)$$

where,

- T : temperature
- h : a coefficient depending on the hardness
- P_0 : penetration at $T = 0^\circ\text{C}$
- P : penetration at the required temperature

The value of penetration is an indication of the resistance to deformation and closely related to the viscosity.

2.2.3 Softening Point

The bitumen has no well – defined melting point. When heated it gradually softens [3]. In very hard binders the penetration value may come out to be zero. Besides, an average penetration may be difficult to determine , should the binder be highly sensitive to temperature. In such cases the consistency can be determined from the ring and ball method. In this method, the temperature at which a standard iron ball

punches through a binder membrane is measured. This temperature value is so called as “softening point”.

2.2.4 Fraass Point

Fraass Point determines the behaviour of the asphalt at low temperatures. At the breaking point temperature, determined by the Fraass Method, the stretch (flexibility) of the bituminous material reduces and it comes to brittle state. On a steel plate of dimensions of 41x20mm, approximately a 5 mm thick asphalt film is laid.

The limit temperature which defines the transition from brittle-elastic state to elasto-plastic state is the “Fracture point-brittleness temperature”, as defined by Fraass method. Softening point, however, is the limiting temperature defining the transition from elasto-plastic state to visco-elasto-plastic state, and is determined by the ring and ball method.

At temperatures below fracture point (Fraass point), i.e. in brittle elastic range, it is essential that the variation of the elastic modulus of the asphalt with temperature be investigated. In elasto-plastic range, however, the tensile resistance of the asphalt is the determining parameter. The variation of viscosity with temperature must be determined in both visco-elastic and full viscous range.

2.2.5 Sensitivity of Asphalt to Temperature

Sensitivity indicates the change of the consistency of an asphalt mixture. Because consistency is determined from viscosity or penetration, sensitivity is defined as the absolute value of the derivative of either of these quantities with respect to time. In this case we have two definitions for sensitivity, namely σ_v for viscosity and σ_p for penetration :

$$\sigma_v = \left| \frac{d\eta}{dt} \right| \quad (2.9)$$

$$\sigma_p = \left| \frac{dp}{dt} \right| \quad (2.10)$$

where,

P : Penetration

η : Viscosity

2.2.6 Ductility

Ductility is a measure of the stretch ability under slowly applied loads. It is considered to be an important characteristic of asphalt cements by some engineers. Some asphalt cements having an exceedingly high degree of ductility are also more temperature-susceptible. That is, the change in consistency with temperature is large.

Ductility of an asphalt cement is measured by an “extension” type of test where a standard briquette of asphalt cement is moulded under standard conditions and dimensions. It is then brought to standard test temperature, normally 25°C. One part of the briquette is pulled away from the other at a specified rate, normally 5 cm per minute until the thread of asphalt connecting the two parts of sample breaks. The elongation (in centimetres) at which the thread of material breaks is designated as the *ductility* of the asphalt [1].

2.3 POLYMERS

Polymers are made up of repeating units formed from monomers, which are linked together through a chemical process known as polymerisation. Homopolymerization is a process in which only one type of monomer molecule is used to form a polymer, resulting in the formation of homopolymers. The process is called copolymerization when more than one chemical species is used as a monomer. Through controlling the type and degree of copolymerization, the properties of the copolymer may be varied.

One of the most important performance characteristics of polymers is the marked dependence of their properties on temperature within their useful temperature range. The useful temperature range of a polymer may be raised with the addition of suitable cross-linking monomers having a higher useful temperature range.

Numerous materials can be classified as polymers. These include natural rubber, synthetic rubber, vulcanised rubber, unvulcanised rubber, neoprene, other styrene-based materials, block copolymer, reclaimed rubber, as well as various plastics polyethylene, polypropylene. Some polymers are available in crumb form, some as an emulsion and others as oil soluble solutions. Generally speaking, two types of polymers are used, plastomers (or thermoplastic polymers) and elastomers.

2.3.1 Plastomers

This group of polymers includes among others ethylene-vinyl acetates (with varying contents of vinyl acetate) and polyolefins such as polyethylene, atactic polypropylene and polyethylene-propylene-diene [4].

Except for ethylene-vinyl acetate, these polymers do not improve the properties of bitumens at low temperatures. They are used in :

- emulsions of pure or cut-back binder for surface dressing,
- porous asphalt mixes,
- thin bituminous surfacings,
- cold-laid bituminous mixes,
- certain bituminous mixes on highly deformable underlying layers,
- preformed or cast-in-place waterproofing systems.

2.3.1.1 High Density Polyethylene

High Density Polyethylene possesses different chemical and physical properties from the other polymer types.

2.3.1.1.1 Chemical Properties

Comparable to the properties of conventional asphalt cement, as an additive, polyethylene behaves somewhat differently than other polymeric or elastomeric additives. Most of these materials are processed to produce a complete homogeneous dissolution of the additive in the asphalt cement. Polyethylene does not dissolve in asphalt cement, but forms a uniform dispersion of micron-size particles.

2.3.1.1.2 Physical Properties

The High Density Polyethylene(HDP) have higher molecular weight than the constituents of asphalt cement. The long-chain, largely crystalline polyethylene acts as reinforcement to the amorphous low molecular mass of the asphalt cement. They improve rheological properties. Also, the long flexible chains of the polyethylene molecules attach themselves firmly to the surface of the mineral aggregates, thus increasing adhesion of the binder to the aggregate matrix.

2.3.2 Elastomers

In this family of polymers a distinction is made between new elastomers such as styrene-butadiene-styrene with 30% of styrene (linear or stellate), polyisoprene, chloroprene (neoprene), rubber emulsions, and recycled elastomers such as powdered rubber from worn tyres. They are used in :

- emulsions of pure or cut-back binder for surface dressing,
- surface dressings, even on high volume roads,
- thick surface dressings,
- stress-absorbing membrane interlayers (SAMI) for waterproofing and against reflective cracking,
- porous asphalt mixes,
- tack coats for thin bituminous surfacings,
- bitumen-based slurry seals,

- waterproofing systems

2.4 POLYMER MODIFIED BITUMENS

As the bitumen is responsible for the visco-elastic behaviour characteristic of all bituminous materials, it plays a large part in determining many aspects of road performance. Resistance to permanent deformation and cracking are typical examples. In general the proportion of any induced strain in a bituminous material that is attributable to viscous flow, i.e. non-recoverable, increases with both loading time and temperature. The effect of this is illustrated in Figures 2.1 and 2.2 [5]. Figure 2.1 shows the response of a bituminous material to a simple creep test. The strain resulting from the applied loading shows an instantaneous elastic response followed by a gradual increase in strain with time until load is removed. The change in strain with time is caused by the viscous behaviour of the material. On removal of the load, the elastic strain is recovered instantaneously and some additional recovery occurs with time. This is known as delayed elasticity. Ultimately, a permanent residual strain remains which is irrecoverable and is directly caused by viscous behaviour. The response to a load pulse induced in an element of a bituminous material due to moving traffic loads is shown in Figure 2.2. Here it is not possible to distinguish between the two components of elastic response, but the small permanent strain illustrated in Figure 2.1 is small for a single pulse load, when many millions of load applications are applied to a pavement, a large accumulation will develop and this is the component which results in surface deformation [5]. From the above it is clear why more deformation occurs at high ambient temperatures and where traffic is slow moving or stationary. One of the prime roles of a bitumen modifier is to increase the resistance of the asphalt to permanent deformation at high road temperatures, without adversely affecting the properties of the bitumen or asphalt at other temperatures. This is achieved by either stiffening the bitumen so that the total viscoelastic response of the asphalt is reduced, with a corresponding reduction in permanent strain, or by increasing the elastic component of the bitumen, thereby reducing the viscous component, which again results in a reduction in permanent strain.

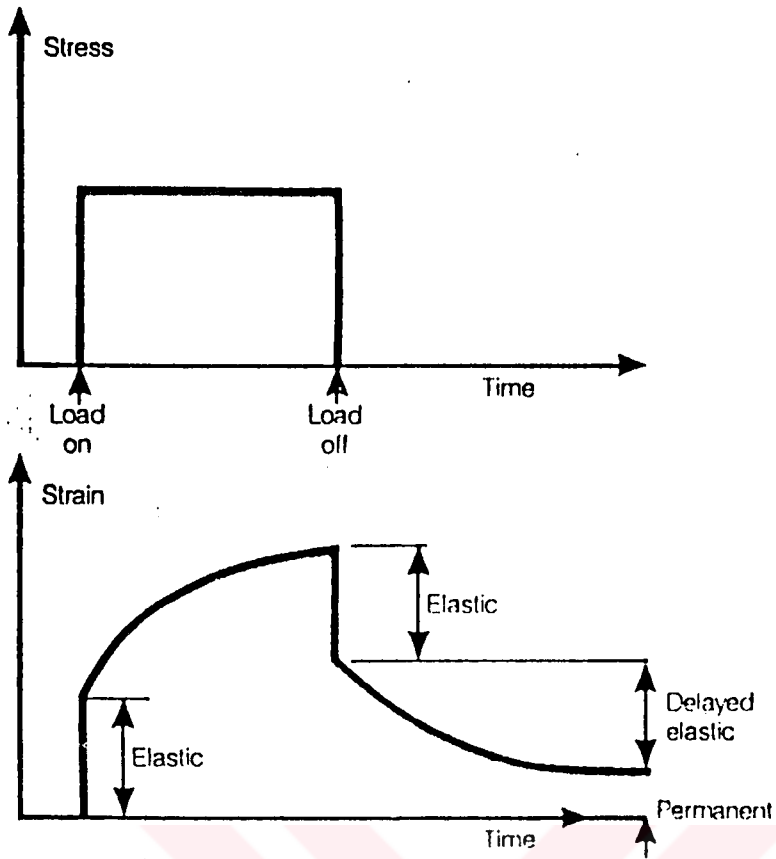


Figure 2.1 Visco-elastic response to static loading

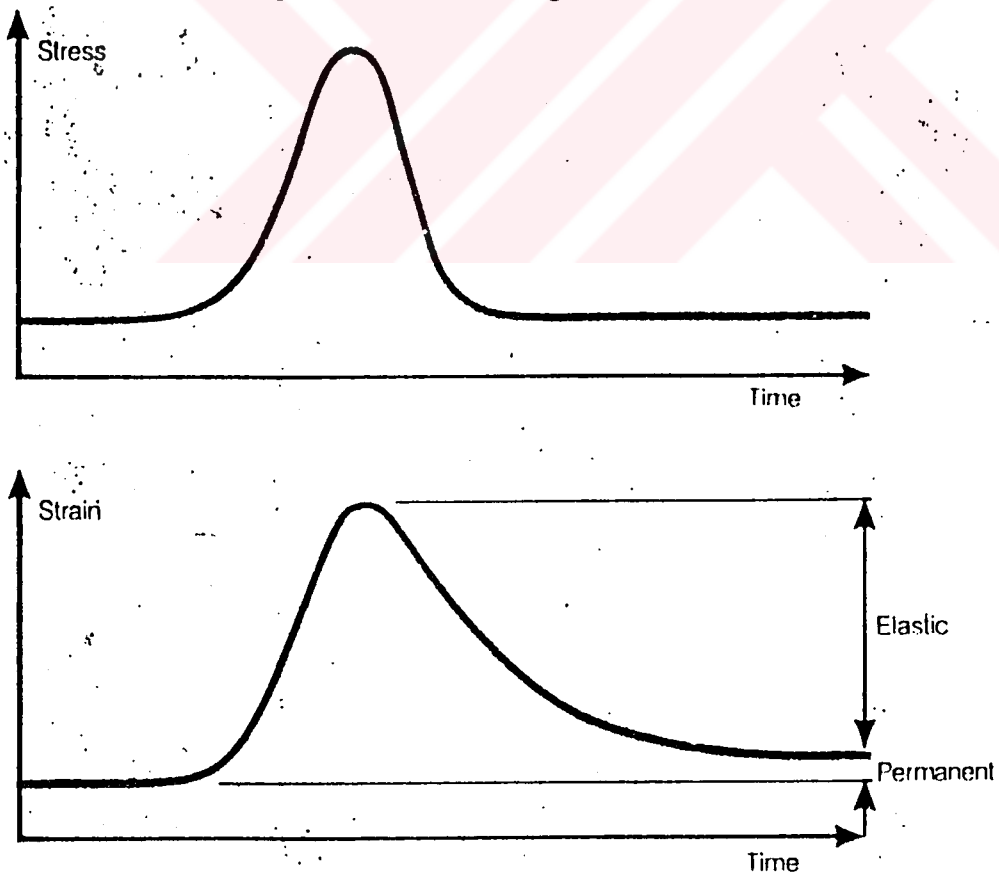


Figure 2.2 Visco-elastic response to a moving wheel load

Increasing the stiffness of the bitumen is also likely to increase the dynamic stiffness of the asphalt, thus improving the load spreading ability of the material and increasing the structural strength and expected design life of the pavement; alternatively it may be possible to achieve the same structural strength but with a thinner layer. Increasing the elastic component of the bitumen will improve the flexibility of the asphalt which is important where high tensile strains are present [6].

2.4.1 The Modification of Bitumen

For many years researchers and chemists have experimented with modified bitumens, mainly for industrial uses, adding asbestos, special fillers, mineral fibres and rubbers. In the last twenty years many researchers have looked at a wide spectrum of modifying materials for bitumens used in road construction.

For the modifier to be effective and for its use to be both practicable and economic, it must have following characteristics [7] :

- be readily available;
- resist degradation at asphalt mixing temperatures;
- blend with bitumen;
- improve resistance to flow at high road temperatures without making the bitumen too viscous at mixing and laying temperatures or too stiff or brittle at low road temperatures,
- be cost effective.

The modifier when blended with bitumen should have the following characteristics:

- maintain its premium properties during storage, application and in service
- be capable of being processed by conventional equipment
- be physically and chemically stable during storage, application and in service
- achieve a coating or spraying viscosity at normal application temperatures.

2.4.2 Modification of bitumen by the addition of thermoplastic polymers

Polyethylene(PE), polypropylene, polyvinyl chloride(PVC), polystyrene and ethylene vinyl acetate (EVA) are the principal thermoplastic polymers which have been examined in modified road binders. As thermoplastics, they are characterised by softening on heating and hardening on cooling.

Thermoplastic polymers, when mixed with bitumen, associate at ambient temperature, increasing the viscosity of the bitumen. Unfortunately they do not significantly increase the elasticity of the bitumen and when heated they can separate, which may give rise to a coarse dispersion on cooling [8].

The concept of modifying asphalt binders and mixtures is certainly not new, but has become much more prominent during the past few years. One reason for this resurgence in interest has been the changing process of how oil refineries obtain and process crude oil. Following the 1973 Arab oil embargo, the traditional sources and supply lines changed. Many refineries that were accustomed to a single crude oil from multiple sources. These changes made it more difficult to meet specifications for paving grade asphalt cement. This situation provided additional opportunities for enhancing asphalt cement through modification, for example.

Other factors that may have some influence on an increased interest in modifying asphalt cement include at least the following:

- there is a potential for the prices of crude oil and asphalt cement to rise
- the U. S. A. paving industry, including Hot Mix Asphalt (HMA) production, has changed to accommodate the shift from larger projects such as the Interstate System to smaller projects such as maintenance of the existing road network.
- higher cost have created a tendency to construct thinner pavements, thus reducing service lives.
- traffic factors have increased; including heavier loads, higher volume and higher tire pressures.
- deferred maintenance has occurred because of funding shortages.

- there have been many construction equipment modifications, such as the introduction of drum mix facilities, use of higher quantities of fines (- #200 sieve size), lower mixing temperatures, use of baghouses and baghouse fines, more extensive use of steel wheel and vibrating rollers.
- the need for special situations such as resistance to fuel spillage.
- environmental and economic pressure to dispose of certain industrial waste materials (i.e., tires, glass, ash, etc.) has prompted the idea of converting them to asphalt cement additives.

Because some of these problems existed in Europe prior to their emergence in the U.S., there was an earlier move toward asphalt modification. Also, some countries require contractor guarantees for performance and this promoted the use of modifiers in an attempt to ensure better performance and to lower life cycle costs. This approach is in contrast to the U. S. where low initial cost is the governing factor in the existing bid process.

A family of products and process are aimed at a variety of pavement applications. The highway engineer knows that the complexity of pavement distress requires a choice of repair or rehabilitation options, one or two methods may not suffice. The appropriate modification of asphalt binders has broadened the choices available to the engineer. Although conventional paving asphalt cements are adequate for many applications, it has been suggested that asphalt cement will become the raw material for the next generation of pavement binders. In fact, one of the more common approaches to modification is to blend asphalt cement from two or more crude sources. Although this practice is often satisfactory, it can also lead to problems of chemical incompatibility of asphalt cements [9].

Engineers who are familiar with the field performance of HMA pavements generally agree on three potential modes of distress:

1. Permanent deformation

- Distortion or shoving
- Rutting

2. Cracking

- Repeated load (fatigue cracking)
- Non-load (thermal cracking)

3. Disintegration

- Raveling
- Stripping (moisture damage)

Although most HMA pavements perform satisfactorily, problems still do occur. Consequently, there is an increased interest in making changes that include several possibilities:

- Improved pavement design (structural, drainage, materials etc.)
- Revision of specifications for paving materials and pavements
- Improvement in the quality control of construction
- Improvement of binders systems

An ideal pavement binder would be modified to achieve several improvements. They have :

- higher stiffness at high temperature conditions (summer) to reduce rutting and shoving, and to improve the fatigue life of HMA pavements
- lower stiffness in low temperature conditions (winter) to reduce thermal cracking
- lower stiffness (or viscosity) during the construction phases to expedite pumping of HMA, and they increase adhesion between the binder and aggregate in the presence of moisture to reduce stripping. Traditionally, changing mixture properties to accommodate different situations has been achieved by mix design and by changing grades of asphalt cement, but the advent of using modifiers opens up new possibilities [9].

2.4.3 Properties of Polyethylene Modified Hot Mix Asphalt

The polyethylene modification process incorporates approximately 4-6% polyethylene in asphalt cement, which is then combined with aggregate to produce the paving mixture. The stability and durability of the HMA pavement over the ambient temperature range are improved considerably, resulting in longer service life, economical use of paving materials, reduced maintenance costs, and an improved riding surface. The use of recycled polyethylene contributes to the management of plastic waste, which is a major concern to Environment authorities.

2.4.4 Mixing of Polyethylene Modified Bitumen with Aggregate

Mixing of the Polyethylene Modified Bitumen with aggregate is done in the conventional manner. No additional equipment is required. Both drum plants and batch plants may be used. A mixing temperature that is slightly higher than normal may be required, depending on the viscosity of binder and the desired Laydown temperature.

2.4.5 Laydown and Compaction

The pavement construction is also carried out in the conventional manner, with no additional equipment required. Because of the higher viscosity of the binder, the Laydown temperature should be about 20-30°C higher than normally used for unmodified mixes. The recommended initial breakdown compaction should occur between 145°C and 155°C. Compaction of the HDP modified hot mix asphalt at temperatures below 135°C will be largely ineffective due to the crystallization point of the polyethylene additive.

CHAPTER 3

RESILIENT MODULUS OF ASPHALT CONCRETE

3.1 INTRODUCTION

Several test procedures and theories for determining the different moduli of asphalt mixtures have been developed. Among these moduli are Young's modulus, the resilient modulus, the complex modulus, the modulus obtained from the Shell nomograph, and the dynamic modulus. Among these moduli, the resilient modulus has gained popularity as a means of evaluating the response of asphaltic mixtures to loads. In the 1994 AASHTO Design Procedures For New Pavements, the basis for material characterization is the resilient modulus [10]. The values of the resilient modulus (M_R) can be used to evaluate the relative quality of materials as well as the input value for pavement design or pavement evaluation and analysis [11].

The diametrial resilient modulus test is a nondestructive test which allows the testing of the specimen under different conditions to eliminate the specimen-to-specimen variation. This test is basically a repetitive load test using the stress distribution principles of the indirect tensile test [12]. In its current form, the diametrial resilient modulus test consists of compacting mix specimens, conducting a density-void analysis on compacted specimens and testing the compacted specimens for their resilient moduli. Details of the test procedure and equipment required are documented in ASTM D 4123-82.

3.2 RESILIENT MODULUS

The elastic modulus, or Young's Modulus of elastic material is defined as :

Modulus = Stress/Strain

Where the strain is not a function of loading time. However, when testing viscoelastic materials, the same relationship applies, but the loading duration of the test must be defined because short loading time gives a much higher modulus value than a long loading time. This is because the viscoelastic material will flow more freely as the loading time increases. Since the asphalt mixture is a viscoelastic material, its stress-strain characteristics, described by its modulus, are time dependent. A modulus that is time dependent is referred to as a stiffness modulus; *if the loading time is short, it is referred to as modulus of resilience.*

A review of the literature indicates that the modulus of resilience is the most common idealised modulus used in characterising asphalt mixtures. The modulus of resilience is defined as the ratio of applied stress to recoverable strain when a dynamic load is applied for a short loading time [12]. It can be expressed as

$$M_R = \sigma/\epsilon \quad (3.1)$$

where;

M_R : Resilient Modulus (MPa)

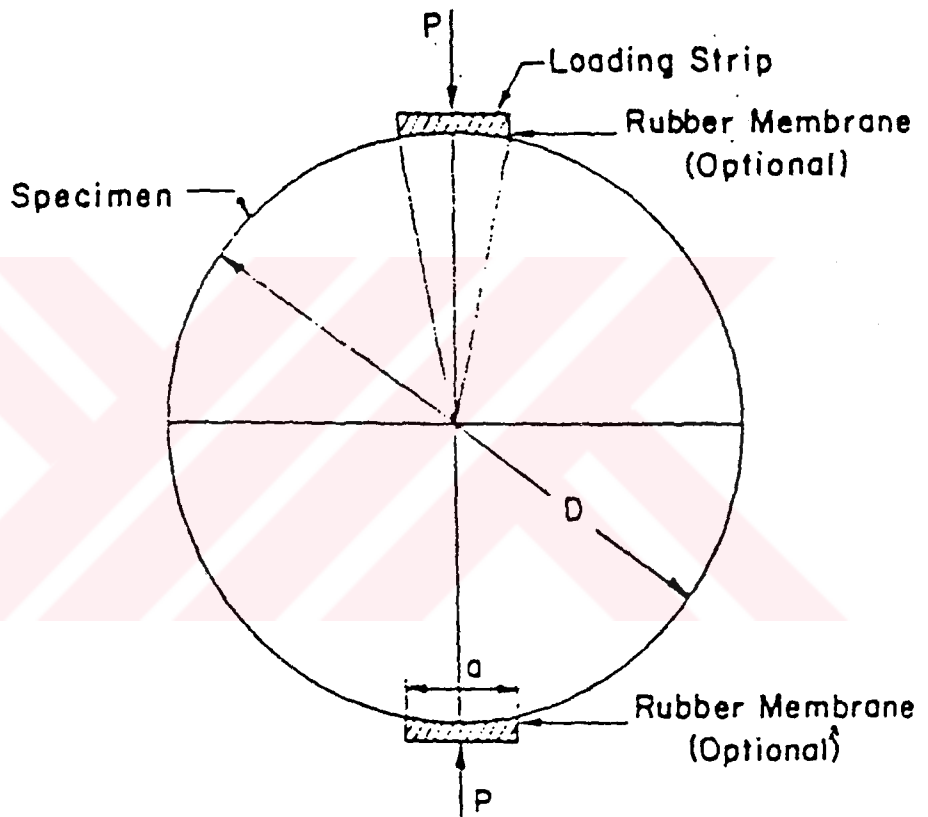
σ : Applied stress (MPa)

ϵ : Recoverable strain

The expression is based on the assumption that when viscoelastic material is loaded for a short duration of time, its response is mainly elastic.

Reviewing the literature further indicated that currently the modulus of resilience is often determined using different procedures such as the direct compression test [13, 14], the indirect tension test [15], the torsion test and the direct tension-compression test [16].

The last two test methods are somewhat complicated, time consuming and expensive, while the direct compression test and the diametrial test methods are simple to run. Both test methods are based on the fact that when viscoelastic material is loaded for a short period of time, its response is mainly elastic. The test involves applying a cyclic pulse load of short duration to the test specimen and measuring the instantaneous deformation. The resilient modulus is then calculated from the applied stress and the measured recoverable strain. The resilient modulus is essentially the instantaneous elastic modulus of the viscoelastic materials. The diametrial test method is preferred over other modes of repeated load tests because it is simple to run and requires a Marshall size specimen. In this research, the diametrial test method was selected primarily because it is more sensitive to the effect of binder on the mixture than the direct compression test. This is because when an asphalt mixture is under compression, the shearing stress is resisted by both aggregate interlock and the asphalt stiffness; on the other hand, when the asphalt paving mixture is in tension, the effect of aggregate interlock is much less. The diametrial resilient modulus test method developed by Schmidt [17] and described in the ASTM Method D 4123-82 was used in this research. The test is conducted by applying a vertical pulse load of certain duration. Diametrically on a Marshall-sized specimen and recording the corresponding horizontal deformation. The theoretical base of the equation calculating the resilient modulus from the applied load and the induced horizontal deformation was based on the analytical work of Timoshenko [18] and Frocht [19] on an elastic disk, with the assumption that the material is linearly elastic and in plain stress condition. Based on their works, Schmidt [20] derived the following relationship between the resilient modulus and the induced horizontal deformation of the specimens in the diametrial resilient modulus test. The test has many advantages, the most obvious being simplicity of test procedure (Figure 3.1). The theoretical distribution of stresses for a concentrated load is shown in Figure 3.2.



- = applied load
- = thickness of specimen
- = diameter of specimen
- = width of loading strip
- = 0.5 in. (13 mm) for 4-in. (102-mm) diameter specimen
- = 0.75 in. (19 mm) for 6-in. (152-mm) diameter specimen

Figure 3.1 Indirect Tension Test

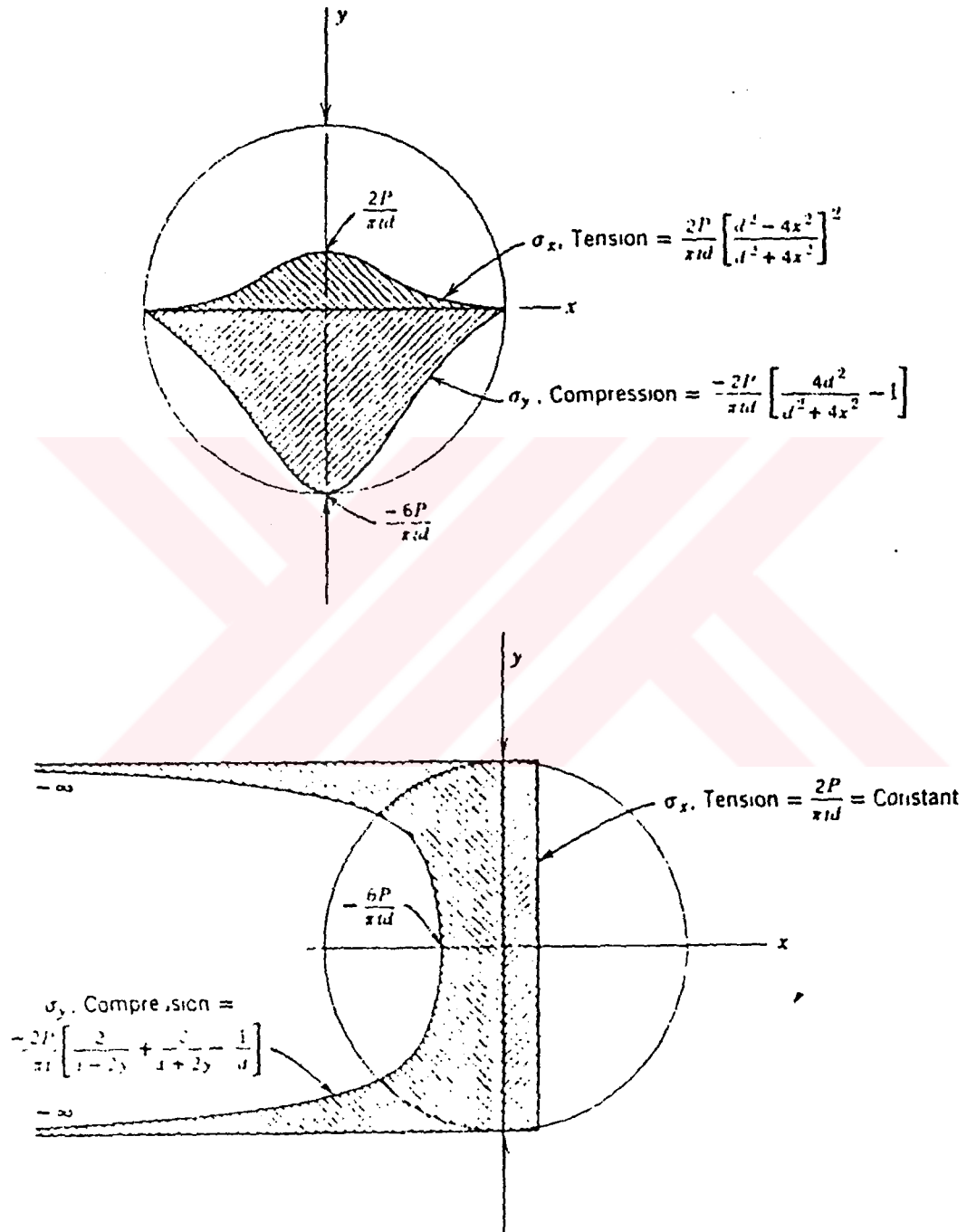


Figure 3.2 Theoretical stress distribution on horizontal and vertical diametrical planes for indirect tensile test. (From Frocht.)

For the horizontal diametrial (diameter) plane, the state of stress is given by equations 3.2 to 3.5 For the vertical diametrial plane (along the load axis), the stresses are shown by equations 3.6 to 3.8.

Horizontal diametrial:

$$\sigma_x = \frac{2P}{\pi t d} \left[\frac{d^2 - 4x^2}{d^2 + 4x^2} \right]^2 \quad (3.2)$$

$$\sigma_y = -\frac{2P}{\pi t d} \left[\frac{4d^2}{(d^2 + 4x^2)} - 1 \right] \quad (3.4)$$

$$\tau_{xy} = 0 \quad (3.5)$$

Vertical diametrial :

$$\sigma_x = \frac{2P}{\pi t d} = \text{Constant} \quad (3.6)$$

$$\sigma_y = -\frac{2P}{\pi t} \left[\frac{2}{d - 2y} + \frac{2}{d + 2y} - \frac{1}{d} \right] \quad (3.7)$$

$$\tau_{xy} = 0 \quad (3.8)$$

where,

σ_x : the tension stress (psi)

σ_y : the compressive stress (psi)

P : total applied load (lb)

t : specimen thickness (in.)

d : specimen diameter (in.)

x, y : coordinate values from center of specimen

The σ_x and σ_y distribution for an idealized elastic material subjected to a diametric load have been presented in equations 3.2 and 3.4. Assuming that plane stress conditions are applicable ($\sigma_z = 0$) the resultant strain ε_x is given by

$$\varepsilon_x = [\sigma_x - \mu\sigma_y] \quad (3.9)$$

Substitution of equations 3.2 and 3.4 into 3.10 results in :

$$\varepsilon_x = \frac{2P}{E\pi t d} \left[\frac{d^4(1+5\mu) - 8x^2d^2(1-3\mu) + 16x^4(1+\mu)}{(d^2+4x^2)^2} \right] \quad (3.10)$$

The deformation across the horizontal diametrial ($y=0$) may be found by integrating equation (3.10) between $x = -d/2$ and $x = d/2$. This results in the horizontal deformation being equal to

$$\Delta H = \frac{P}{tE} \left[\frac{4}{\pi} + \mu - 1 \right] \quad (3.11)$$

Thus, for an applied dynamic load of P in which the resulting horizontal dynamic deformation is measured, the modulus or M_R value is :

$$M_R = \frac{P(\mu + 0.2734)}{t\Delta H} \quad (3.12)$$

where,

M_R : Modulus of resilience (MPa)

P : Applied load (Newton)

μ : poisson's ratio (A commonly used value of Poisson's ratio for asphaltic materials is 0.35. Deviations from this value result in nonexcessive errors in the calculated M_R)

ΔH : horizontal deformation, (mm)

t : thickness of diametrial specimen, (mm)

For asphalt paving mixtures, Schmidt suggested 0.35 to be used as the poisson's ratio, while Kennedy calculated the poisson's ratio by measuring both horizontal and vertical deformation and found Schmidt's suggestion to be reasonable [21].

3.3 THE RELATION BETWEEN RESILIENT MODULUS AND STRUCTURAL LAYER COEFFICIENT

The structural layer coefficient (a_i) for Asphalt Concrete (AC) was introduced in 1972 AASHTO Interim Design Guide to select AC thicknesses. This coefficient is a measure of the relative ability of a unit thickness of a given material to function as a structural component of the pavement. The layer coefficient concept as used in the AASHTO Design Guide is based on empirical results from the AASHO Road Test. While layer coefficients are an indication of a material's ability to carry loads, they do not directly relate to the material's "strength". However, since strength measurements are much more readily obtained and more easily understood, layer coefficients are typically estimated from correlations in terms of strength values. With the resilient modulus test more prevalent the relationship shown in Figure 3.4 can be used to relate the modulus to the structural layer coefficient. Different mixes have different modulus values, and hence different effects in the design process. Every mix should be so investigated as to determine the proper relationship to use [10].

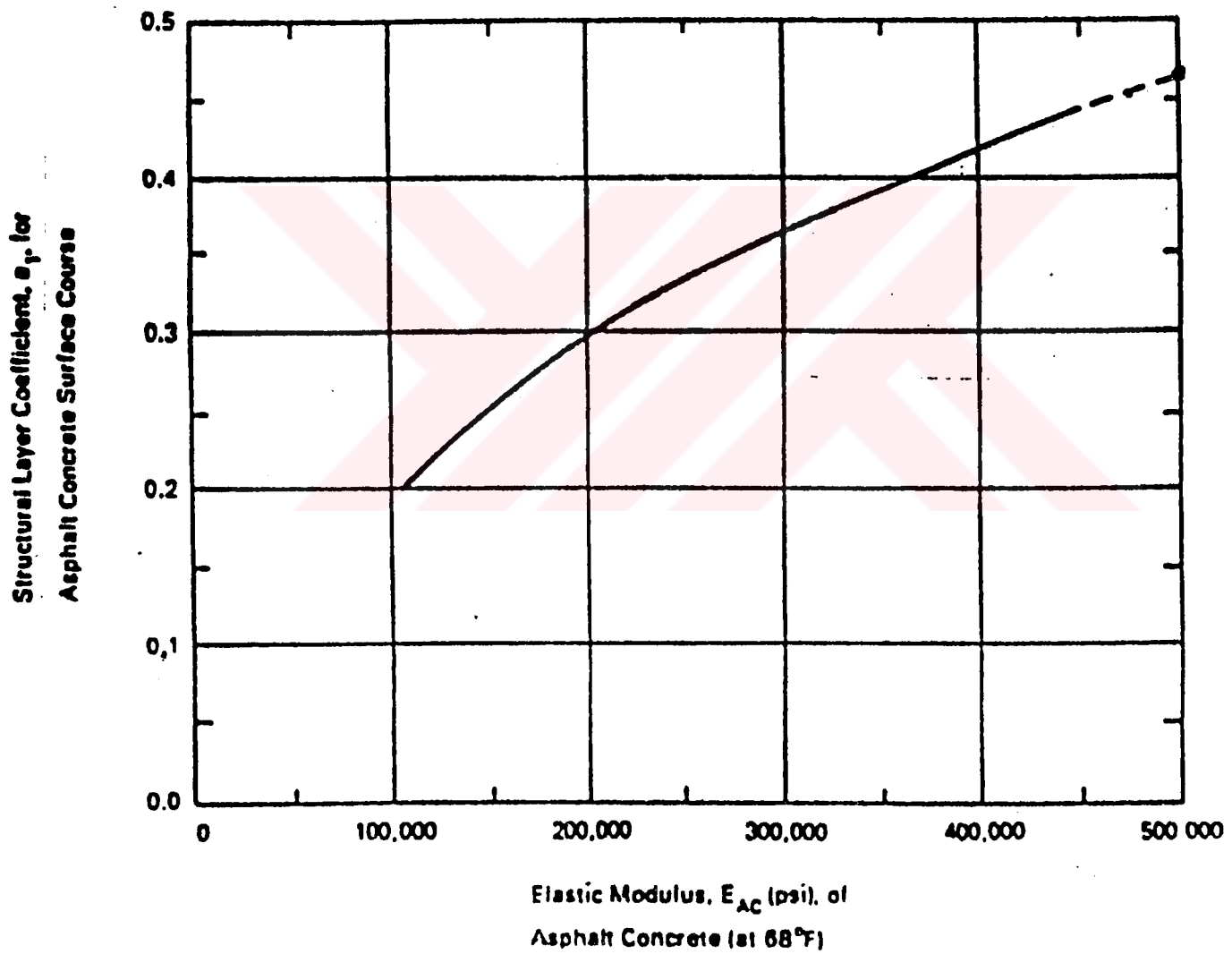


Figure 3.4 Chart for estimating the structural layer coefficient of dense-graded surface course based on the elastic(resilient)modulus (Van Til et al. 1972)

CHAPTER 4

POLYMER MODIFIED ASPHALT CONCRETES

4.1 INTRODUCTION

Polymers are made up of repeating units formed from monomers, which are linked together through a chemical process known as polymerisation. Homopolymerization is a processing in which only one type of monomer molecule is used to form a polymer, resulting in the formation of homopolymers. The process is called copolymerization when more than one chemical species is used as a monomer. Through controlling the type and degree of copolymerization, the properties of the copolymer may be varied.

One of the most important performance characteristics of polymers is the marked dependence of their properties on temperatures within their useful temperature range. The useful temperature range of a polymer may be raised with the addition of suitable cross-linking monomers having a higher useful temperature range.

Numerous materials can be classified as polymers. These include natural rubber, synthetic rubber, vulcanized rubber, unvulcanized rubber, neoprene, other styrene-based materials, block copolymer, reclaimed rubber, as well as various plastics polyethylene, polypropylene. Some polymers are available crumb form, some as an emulsion and others as oil soluble solutions.

4.2 PREVIOUS STUDIES ON THE POLYMER MODIFIED ASPHALT CONCRETE

Reviewing the literature indicated that, in practice, the terms ‘rubber’ and ‘polymer’ are often used interchangeably by pavement engineers. Polymers have been added to asphalt for different uses well over 100 years, and such a wealth of literature exists on the subject that a complete listing and review of all published articles is not feasible or practical. However, an excellent source of information about polymer-asphalt is an annotated bibliography on the use of rubber in asphalt pavement prepared by Rostler [22].

Natural polymer is commonly known as natural rubber and it is chemically defined as poly (isoprene). It is commercially available in a variety of grades, qualities and shapes. Synthetic polymer is also chemically defined as a poly, but not an exact duplicate of natural polymers are large molecules formed by the joining together of hundreds to thousands of small molecules in long chains. The chemical makeup of polymer varies from a hydrocarbon-type compound to complex reaction products containing many elements. Polymer may also be compound with other materials to form fibres, films, or sheets. It may also be vulcanised (cross linked between long chains) to form a tough product or partially vulcanised to form a three-dimensional link between long chains. The situation is even more complicated with respect to styrene-butadiene polymer (SBR) because the difference in ratio of styrene to butadiene, the use of different antioxidants, soap types and contents and many other variables in the polymerisation process result in the production off too many SBR’s and new ones continually develop. Polymer is commercially produced as a fine dispersion or emulsion in water (latex), as a fine dispersion or solution in an organic solvent (resin), or as dry powder or crumb. Latex has been commercially produced for use in asphalt-pavement from natural rubber, vulcanised polymer, neoprene and SBR.

The amount and degree of polymer dispersion into the asphalt binder depend mainly on the desired effect the polymer is to achieve in reinforcing the binder. Polymer can be completely incorporated into the binder and become an integral part of it, partially

integrated into the binder, forming a network between the binder and the aggregate or can act as an elastic aggregate. It is usually assumed that when the polymer is introduced into the asphalt in the form of latex and added in the recommended amount it completely dissolves into the binder.

The degree of dispersion of the polymer particle into the asphalt binder is known to have a major effect on the properties of the paving mixture; however, there is no clear agreement among researchers as to whether full or partial dispersion of vulcanised polymer will result in better pavement performance.

The use of latex was investigated by Gregg [23] where latex was produced from SBR using natural rubber. Gregg reported that the addition of polymer reduced temperature susceptibility as determined from viscosity and penetration. He also reported that premixing of latex with asphalt gave a better result than incorporating latex during the mixing of the polymer dispersion in the binder and performance in fatigue life tests led the author to conclude that high strength is obtained when rubber is presented as a fibrous structure, with gradation of strands ranging from coarse to fine.

Thompson [24] reported that the addition of neoprene to asphalt increases toughness and improves ageing characteristics by decreasing the softening point and penetration and improving temperature susceptibility of the binder. He also reported that asphalts from different sources respond to the same additive in significantly different ways.

Lewis and Welborn [25] found that the characteristics of the polymerized asphalt mixture depend upon the type of polymer (natural, synthetic or vulcanized) and the nature and source of the asphalt.

Early studies suggested that 7.5 to 10 percent of polymer be added to the asphalt. However, as more research was conducted, it was understood suggested that the amount of polymer should not exceed 3 percent of the weight of the asphalt since high amounts of polymer interfere with construction practices [26]. One of the early

problems encountered in preparation of polymerized asphalt paving mixture was that of polymer dispersion throughout the asphalt binder. A number of different approaches have been tried to resolve this problem, including incorporating in the pug mill as a powder or liquid, premixing the polymer with the asphalt binder, or polymerizing the pavement after it has been placed and compacted.

Rostler and White et al., [27] developed a unique method through which the in-place pavement, rather than the asphalt binder or the paving mixture, is polymerized. Through the addition of polymer (terminal-block-butadiene-styrene copolymer, a small amount of which (0.5 to 1.5%) becomes part of the asphalt binder), the asphalt in the in-place pavement is polymerized. The polymer is rubber of high tensile strength in the unvulcanized stage.

Although the use of polymers in asphalt mixture dates back many years, the amount of polymer asphalt pavement construction per year is quite small compared to the amount of conventional asphalt concrete pavement constructed each year.

During World War II, a number of synthetic polymers were developed, some of which have been used with asphalt. In 1948, the Good Year Tire and Rubber Company developed a rubber asphalt which was used in road construction on a large scale in Akron, Ohio [25]. In 1950, Mc Millan and Sommer developed a paving composition consisting of asphalt and butadiene-acrylonitrile rubber [28]. In 1950, Winters [29] reported the use of vulcanized styrene rubber in the form of powder containing barium sulphate with asphalt to improve aging quality and ductility of the binder, where Esch [30] reported the use of vulcanized (reclaimed) rubber in a crumb form to reduce low temperature cracking.

Since the early documented use of polymer or, as it is called, rubber, asphalt rubber has been used mainly in maintenance and rehabilitation operations such as chip seals, joint seals, crack seals, and as a stress-absorbing membrane. Rubber has also been found to perform well as a low modulus stress-absorbing membrane (SAM) or as a stress-absorbing membrane interlayer (SAMI) for aiding in reducing reflection cracking in overlay, while the use of rubber asphalt in joint and crack sealers for

asphalt and concrete pavement has shown its ability to withstand different crack movement, bonding strongly to crack face, and rehealing or rebonding the crack face in warm weather if fracture or separation from crack face occurs [31,32,33,34,35,36].

Styrene-butadiene-styrene(SBS) copolymers have also been added to asphalt which was used for seal coat [37]. It was reported that the addition of SBS improved the binder's temperature susceptibility, cohesion, adhesion to aggregate, and flexibility. Beagle [38] added latex to sand asphalt mixture and used it in field experiments as an overlay. Latex was added to pug mill after the aggregate had been coated with asphalt. The pavement in which latex was used was the highest rated compared to other mixtures in the literature. The author reported that the mixture with latex was least tender and had the best resistance to reflection cracking. However, difficulty in handling and compaction was reported.

Reviewing the literature, one can conclude that all researchers, to one degree or another, agree that the addition of polymer to the binder enhances the elastic response of the binder at high temperature, increases the toughness and adhesion of the mixture, and decreases temperature susceptibility of the binder.

Several factors have resulted in a significant increase in the research and field testing on the use of polymer as a modifier to the binder in hot paving mixture. Among these are rapid advancement of technology in the field of chemical engineering, which has continuously resulted in refinement and development of new polymers; rapid increase in traffic in terms of volume and weight; and new interest among pavement technologists in mitigating poor pavement performance historically attributed to the inherent property of asphalt binder. Study and/or use of paving mixtures which contain polymer now involve a large number of government agencies, universities, and industrial firms [15,17,24].

In recent years pavements have experienced a significant increase of track traffic, tire pressures, and axle loads. While the design of Hot Mix Asphalt (HMA) has served well in the past, new approaches are needed to mitigate premature rutting of heavy duty asphalt pavements.

Polymer modification has been identified as a promising avenue to obtain high performance asphalt pavements [39,40]. Various field Trials within the USA and overseas have shown that such binder systems can be effective in increasing the service life and reducing costs [41].

Polymer modification has been shown to lead to an increase of the rutting resistance as measured in wheel tracking experiments [41, 42]. Valkering et al. reported that at polymer concentrations as low as 3% the number of cycles to obtain 10 mm rut depth could be increased by a factor of 58 [42].

Bouldin. M. C. et al. observed that the wheel tracking test results show that at elevated temperatures (60°C) the mechanical properties of the binder have a significant influence on the rutting resistance of the HMA. Polymer modification leads in the case of the Styrene-rubber block copolymers (SBS) to binder systems with superior rutting resistance compared to the straight asphalt. The rheological ranking agree well with the wheel tracking results, i.e., it is possible to predict the relative performance based on the viscoelastic properties of the binder system [43].

Mayama et al have studied the polymer modified asphalts. They have investigated the effect of polymers and epoxy resin on properties of asphalt. Rheological properties of mixtures were measured and stress-strain relationships in model pavements were analyzed. Mixtures with high viscosity asphalt showed high strength, high modulus and high dynamic stability, and a consequent high deformation resistance to wheel load and low tensile strain in the surface on a model steel plate deck. The failure envelope concept was introduced to find the temperature at which thermal cracking was induced in the surface of a pavement mixtures with low viscosity asphalt showed lower thermal cracking temperature. Relaxation moduli and shift factors obtained from various test methods were similar to each other, and were similar at the specific temperature for each mixture [44].

The stress vs. strain characteristics of asphalts and asphalt concrete mixtures are both time and temperature dependent. Asphalts can be considered to be linear viscoelastic

materials for engineering purposes [29]. For comparatively small strains, asphalt concrete mixtures can be considered to be in this category as well. The balance between the viscous and the elastic nature of the asphalt affects the way a particular asphalt behaves in an asphalt concrete mixture, and this behavior under varying traffic and environmental conditions is important when considering the use of asphalt in pavement construction.

For dynamic testing of asphalt [45,46] and asphalt concrete [13,47,48] in the viscoelastic region, the time(frequency)-temperature superposition principle is applicable. That is, the materials can be considered to be thermo rheologically simple; therefore, the results obtained at higher and lower temperatures can be equated simply and graphically with lower and higher frequencies, respectively. Conversely, results obtained at higher and lower frequencies can be transposed into lower and higher temperatures, respectively.

Many investigators [49,50,51] have studied the performance of asphalt mixtures containing modifiers. It has been generally reported that modifiers enhance mixture characteristics and help mitigate early distress. Goodrich [49], based on a study of polymer modified asphalts, showed that the creep behavior of asphalt concrete mixtures containing specific binders was well correlated with the dynamic rheological properties of those binders.

Shuler et al have studied on the polymer modified asphalts. In their study they have showed that estimating mixing and compaction temperatures for polymer modified asphalts using capillary viscometers could be misleading and might pointed out to higher temperatures than necessary during construction. Stiffness modulus estimated from the Schwyer rheometer indicated that two of the polymers resulted in reduction in stiffness in proportion to the polymer content. An apparent increase in estimated stiffness modulus was observed for only a certain type of polymer. Design asphalt contents in the Marshall method were approximately equal for all mixtures. Marshall stabilities tended to increase for polymer modified mixtures compared with the control mixture. Indirect tensile resilient modulus was not necessarily reduced at low temperatures but increased at high temperatures for polymer modified mixtures.

However, the large alterations in resilient modulus than expected makes judgement of this property difficult for some of the mixtures and suggests that the method be evaluated before additional work using this parameter is to be conducted [52].

Newcomb et al studied polyolefin and latex modified asphalt binders. In this study, modified mixtures made with the same asphalt cement grade showed higher resilient moduli at all temperatures, but the most substantial difference occurred at the higher temperatures, 25 and 40°C. There was a substantial increase in resilient modulus at lower concentrations (less than 10 percent of binder weight) of the modifier, and only a minor gain was obtained with higher concentrations. Large variations were noted in the results between the pavement samples and core samples from the pavement. It was thought that most of these differences were due to the greater air content of the in-place materials [53].

Polymer modified asphalts display more temperature susceptibility as compared to than the unmodified ones. The Oregon Department of Transportation has experienced that polymers are a practical way to improve temperature susceptibility of asphalts. Temperature susceptibility is an important indication of the level of resistance to thermal cracking, and can be easily measured with simple binder consistency tests [54].

Laboratory and field observations indicate that polymerized asphalt mixtures have a greater resistance to permanent deformation (rutting). Polymerized asphalt mixtures are less susceptible to low temperature cracking and more resistant to freeze-thaw damage [55].

Low Density Polyethylene (LDPE) when dispersed in asphalt cement through a high shear blending process produces asphalt concrete mixtures (Novophalt) with superior resistance to deformation at high service temperatures. The dispersion of LDPE within the asphalt results in rheological changes in the binder which not only significantly improve resistance to creep deformation but also improve mixture shear strength. The ratio of induced octahedral shear stress in a paving mixture to the octahedral shear strength of the paving mixture at the specific conditions of loading

is used to demonstrate the ability of Novophalt to reduce deformation potential of asphalt pavements through improved shear strength. The results of the shear strength analysis are corroborated by creep deformation and accumulated permanent strain analyses [56]. Novophalt is a stable dispersion of polyethylene in asphalt cement. It represents the group of modified asphalt where the modifier (polyethylene) does not dissolve in the asphaltic matrix.

In actual road applications [7, 57] the dispersion of polyethylene in asphalt cement is prepared in a special self contained mobile blender equipped with a high shearing action colloidal mill and with auxiliary equipment (storage tanks and pumps).

The introduction of polyethylene (4-7%) stiffens the bitumen, i.e. increases the viscosity and reduces the penetration of resulting binder. Improvements in laboratory measured values of the resistance to permanent deformation and dynamic stiffness of paving mixtures, had been reported [57, 58]. Novophalt binder (Asphalt + Low Density Polyethylene) requires higher manufacturing and compaction temperatures than conventional asphalt. The binder must also be kept stirred to prevent separation of polyethylene and bitumen [58].

Novophalt has the following reported characteristics also [59] :

1. Less temperature susceptibility than original untreated asphalt.
2. Lower sensitivity to heating than original asphalt (as indicated by the thin film oven test).
3. Significant improvement in water resistance for laboratory compacted paving materials.
4. Water resistance is sustained at a wide range of binder content for laboratory compacted mixes.

It is reported that Novophalt has been successfully used by a number of road construction authorities. A number of agencies in Austria, Italy, England, Norway and the United States evaluated this additive both in the laboratory and on test roads.

Changes in Physical and mechanical properties of asphalt and asphalt paving mixtures, when replacing AC 60/70 by Novophalt . These changes can be characterized as :

1. Reduction in penetration and increase in softening point and viscosity.
2. Reduction in Marshall flow and increase in Marshall stability
3. Improvement in water resistance as measured by loss in Marshall stability after 24 hours soaking in water at 60°C
4. Improvement in resilience and split tensile characteristics

These characteristics were almost in complete agreement with those reported in references [14,16,36,60,61]. The improvement of road user comfort associated with environmental protection by waste disposal has been incentive to the modification of bituminous binders by incorporating powdered rubber recovered from used tires. The adhesive properties of rubber-bitumen binders make it possible to construct porous asphalt surfacings the advantages of which lie in easy drainage of surface water, skidding resistance, flexibility at low temperatures, and reduce noise levels [62]

SBS-modified asphalts bring about enhanced qualities, like reduced thermal susceptibility and higher cohesion, hence better resistance to bleeding and aggregate dislodgment. Such improved binders characteristics extend the field of application of chip seals to higher traffic or more difficult road sections. Hot-applied SBS-modified binders have the advantage of developing immediate cohesion as soon as they cool. However, their adhesion to aggregates sometimes difficult or questionable. Moreover, they require a high amount of fluxing agent which may cause severe aggregate embedment and bleeding in hot weather, when the seal has been placed on a bituminous support. Due to these adhesion and viscosity problems, their SBS content must be limited [63].

CHAPTER 5

MATERIALS AND PROCEDURES

5.1 INTRODUCTION

Asphalt concrete consist of binder and well-graded aggregate. The binder may be a normal penetration grade bitumen or a modified bitumen. In this investigation the modifier used consists in High Density Polyethylene(HDP) in the powder form.

This chapter includes the materials and experimental design procedure used to evaluate the effect of mix variables on the properties of HDP modified asphalt concrete. It contains in particular :

- materials used and their properties,
- specimen preparation techniques,
- type of tests
- test procedures.

5.2 AGGREGATE

Any designated gradation of aggregate might be used to evaluate the effect of the modifier on the mechanical properties of the paving mixture. In this research, a typical heavy traffic gradation for hot asphalt mixtures, designated as Type II in the Turkish State Highway Specifications, was adopted [60]. The selected gradation and the specification limits are shown in Figure 5.1

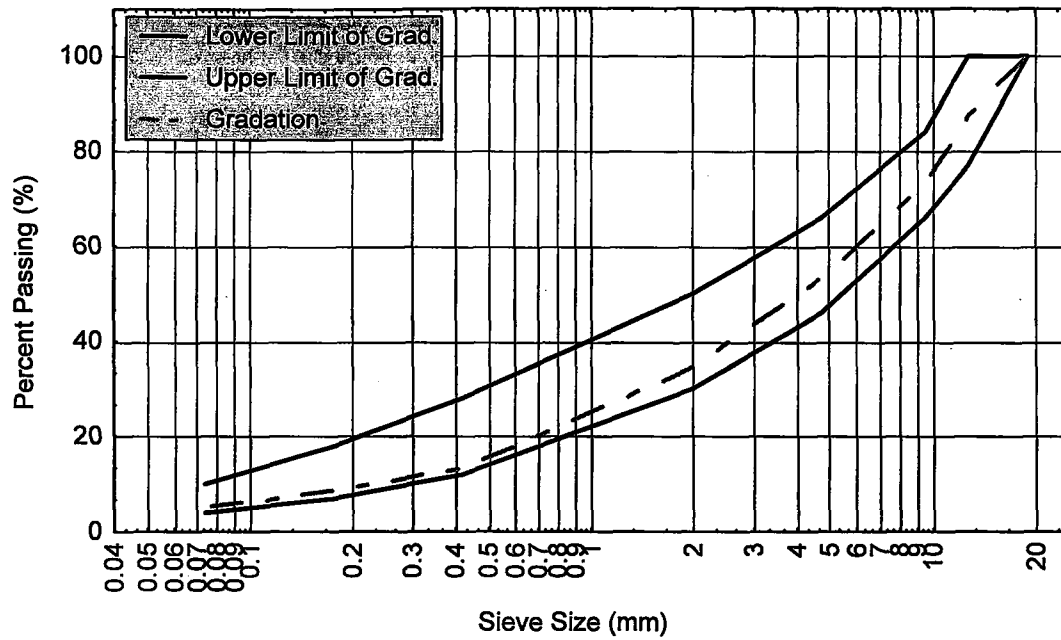


Figure 5.1 Aggregate Gradation For Type II Surface Course

Table 5.1 Gradation used in this study and gradation limits

Sieve Size (mm)	Sieve Size (inches)	Gradation Limits	Used Gradation
19,1	¾	100	100
12,7	½	77-100	87
9,52	3/8	66-84	74
4,76	No.4	46-66	54
2	No.10	30-50	35
0,42	N0.40	12-28	14
0,177	N0.80	7-18	9
0,074	N0.200	4-10	6

The aggregate used was 100 percent crushed limestone supplied by the Makimsan Company. To ensure that the aggregate gradation was the same for each mixture, the aggregate was separated into various sized fractions as designated by the

specifications for Type II for Surface Coarse mix, using standard sieves meeting the requirements of ASTM E 11-87. The various sized fractions were subsequently stored in separate containers until they were recombined in preparing the mixture for the test specimens. In preparing the test specimens mixture, each size fraction of the aggregate was carefully weighted out in accordance with the percentages listed in Table 5.1. In this way, not only was the mixture gradation duplicated, but the percentage of each size used in the mixture was carefully controlled.

The physical properties of the aggregate were determined in the laboratory in strict conformance to ASTM standards. These physical properties were used for calculating the volume of the mineral aggregate and air void in designing the mixture.

Table 5.2 Specific Gravities of Agregate (gr/cm³)

Size Fraction	Apparent Specific Gravity	Bulk Specific Gravity
Coarse Aggregate	2.713	2.682
Fine Aggregate	2.729	2.687
Filler	2.73	-

Other properties of the crushed limestone are as follows :

Frost	: 0% < 12%
Los Angeles Abrasion Test	: 22% < 35%
Flatness	: cubic
Stripping(AC 60/70)	: 60-65 > 50
Organic Material	: None

5.3 BITUMEN

The bitumen used in this study were 60/70 penetration grade bitumen. The bitumen used in this research was supplied by Batman Oil Refinery. This asphalt was

subjected to typical standard laboratory tests to determine its physical properties. The results of these tests are incorporated in Table 5.3.

Table 5.3 Physical Properties of Asphalt Cement Used in This Study

Penetration, 25°C, 100 gr, 5s (1/10mm)	ASTM D5	67
Specific Gravity (gr/cm ³)	ASTM D70	1.047
Flash Point (°C)	ASTM D92	215
Ductility, 25°C, 5 cm/min	ASTM D113	+100
Softening Point (°C)	ASTM D36	56

5.4 HIGH DENSITY POLYETHYLENE (HDP)

The High Density Polyethylene (HDP) used in this investigation was supplied by Petkim Company. The specific gravity of polyethylene was measured to be 0.935 gr/cm³.

After reviewing the work of earlier investigators on the evaluation of the effect of polyethylene on bitumen and bituminous mixtures, the HDP concentrations of 2, 4, 6, 8 % by weight of the bitumen were found relevant for the investigation. In this investigation, the polyethylene was used in powder form. Melting point of HDP was measured to be 180°C. The gradation of HDP used in this study is given in Table 5.4

Table 5.4 The Gradation of High Density Polyethylene

Sieve Size	Percent Passing
No.10 (2 mm)	100
No.40 (0.42 mm)	0

5.5 HDP – BITUMEN BLEND PREPARATION

A speed adjustable vertical shaft mixer with a capacity of 2 liters was used to mix the HDP and bitumen. Temperature control during mixing was achieved by using a thermostat with thermocouple attached to the mixer. The machine was operated at 200 rpm. Considering their deterministic role in the performance of Polymer modified bitumen blends, this study focuses on mixing time and mixing temperature, as suggested by Green et al in 1977 [65]. Three temperatures (145,155,165°C) have been selected as the trial mixing temperatures. The mixing time affects the homogeneity of HDP into the hot bitumen and therefore mixing was carried out for a duration of 5, 15 and 30 minute to assess the effect of mixing time on the properties of the bitumen.

To take full advantage of developments in asphalt technology, designers need a proper understanding of binders and their use. The use of modified binders in bituminous mixtures is likely to gain an increasing popularity in pavement engineering and the knowledge of the rheology of modified binders will allow a good correlation to the behavior of end products.

One of the goals of this research is to determine which properties of HDP modified bitumens offered the best with the performance of asphalt concrete.

5.6 TESTS ON HDP MODIFIED BITUMENS

Three laboratory tests, namely Penetration, Ductility and Softening Point (Ring and Ball) were conducted on all HDP modified bitumen and base bitumen, used in this study. All tests were carried out in accordance with the ASTM standards. The specific gravity and the viscosity values of the modified and unmodified bitumen were calculated. Viscosities of modified and unmodified bitumen were calculated from respect to the equation 2.6 and 2.7. The specific gravity was calculated from the equation 5.1 below.

$$Sg = \frac{100}{\sum \frac{Pw_i}{Sg_i}} \quad (5.1)$$

where,

- Sg : Calculated Specific Gravity (gr/cm^3),
 Pw_i : Percentage weight of components (%),
 Sg_i : Specific Gravity of Components (gr/cm^3).

5.6.1 Penetration

The results of the penetration, as given in Table 5.5 and presented graphically in Figure 5.2 to 5.9 clearly show that the hardness of the binder increased with decreasing mixing time and mixing temperature. As the percentage of HDP increased the penetration decreased. This trend was expected, since in a liquid system viscosity increases as the volume concentration of the solid increases.

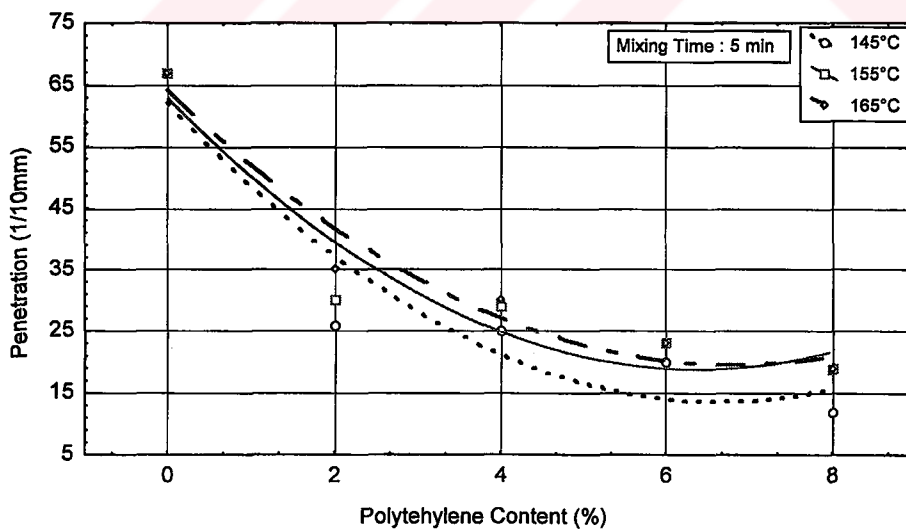


Figure 5.2 Penetration vs Polyethylene content for 5 min. mixing time

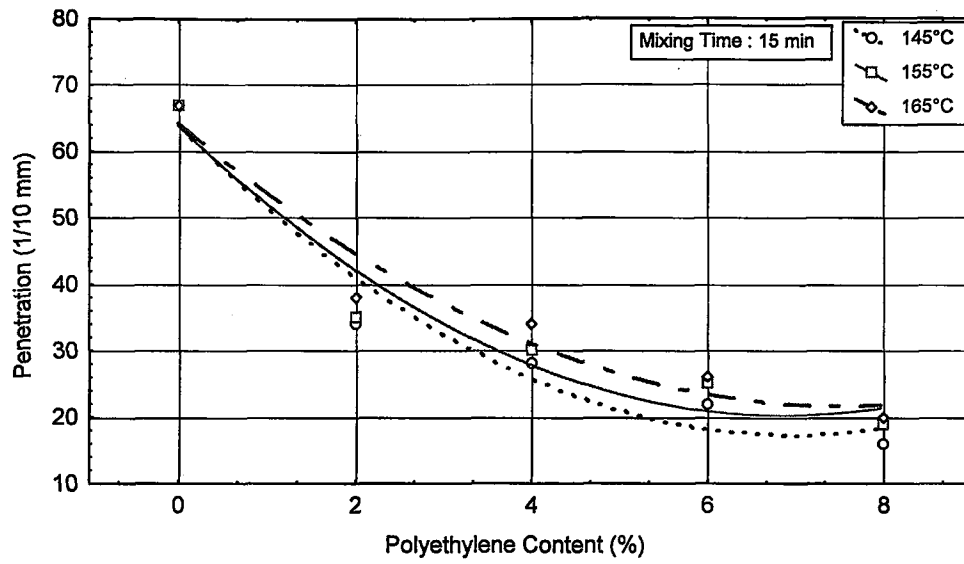


Figure 5.3 Penetration vs Polyethylene content for 15 min. mixing time

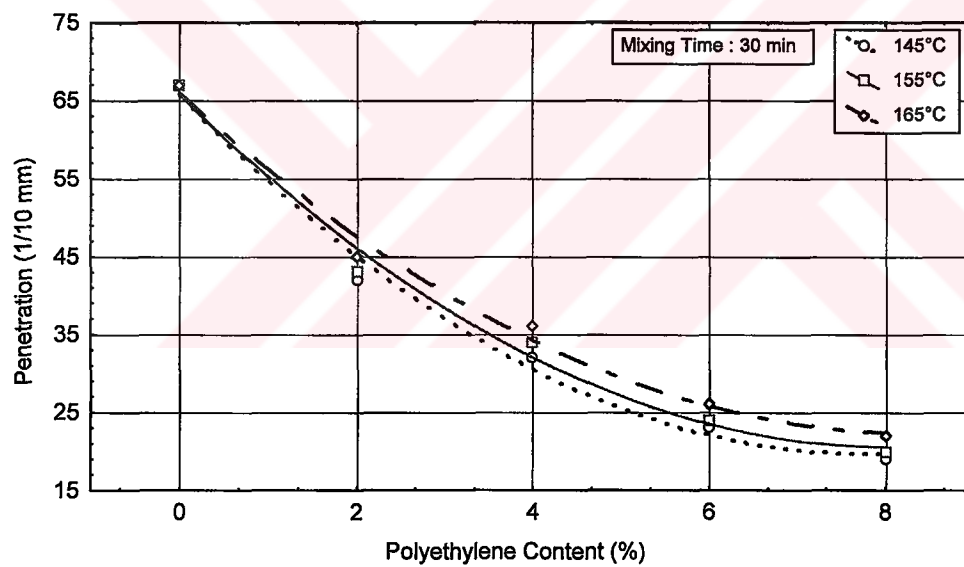


Figure 5.4 Penetration vs Polyethylene content for 30 min. mixing time

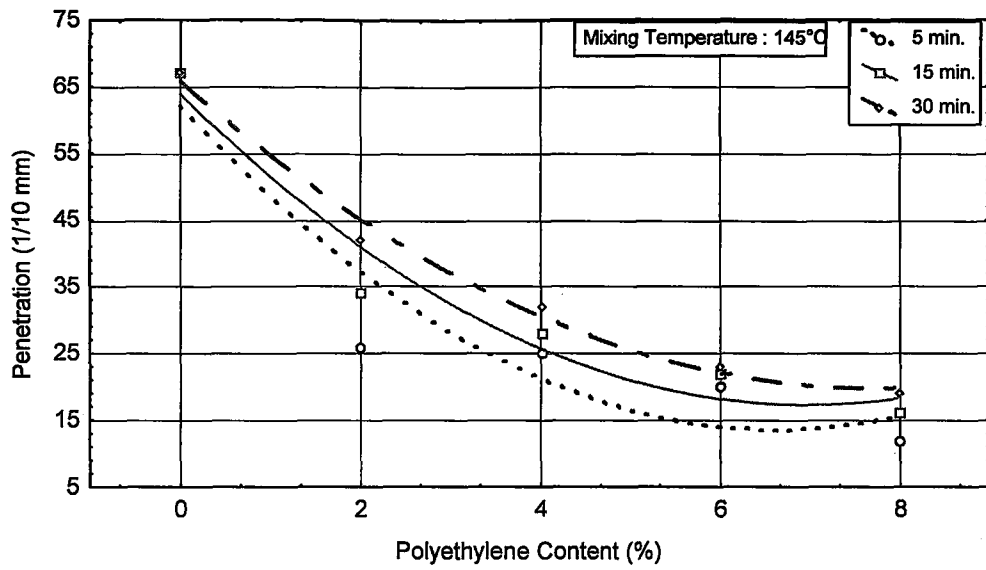


Figure 5.5 Penetration vs Polyethylene content for 145°C mixing temperature

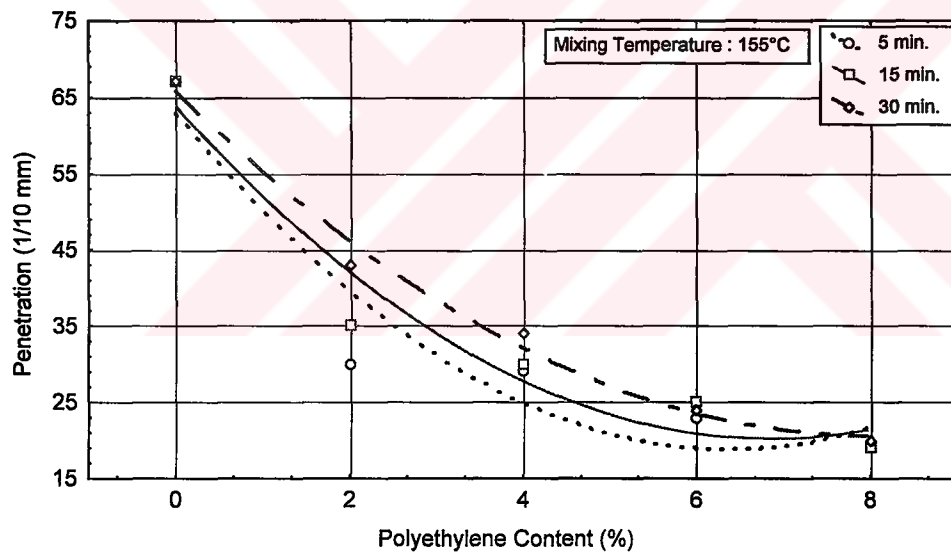


Figure 5.6 Penetration vs Polyethylene content for 155°C mixing temperature

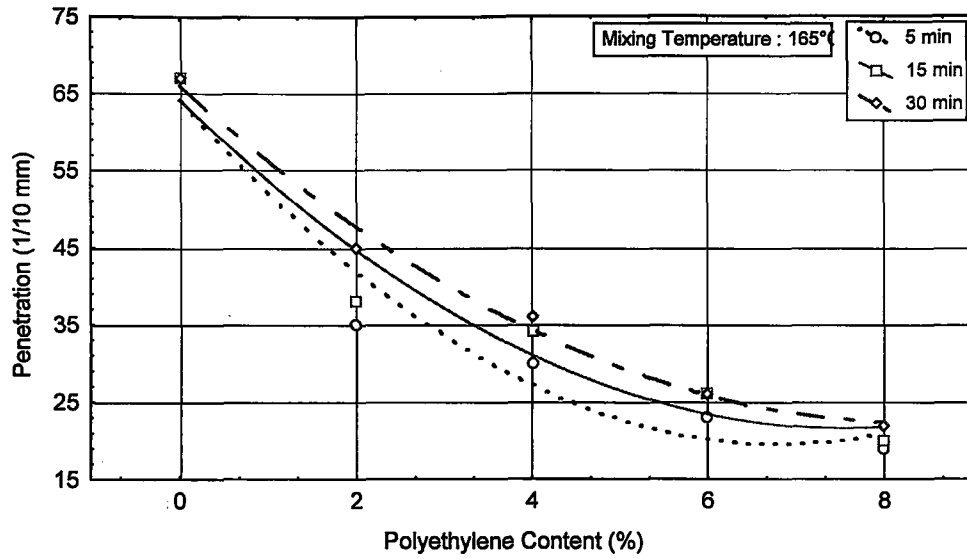


Figure 5.7 Penetration vs Polyethylene content for 165°C mixing temperature

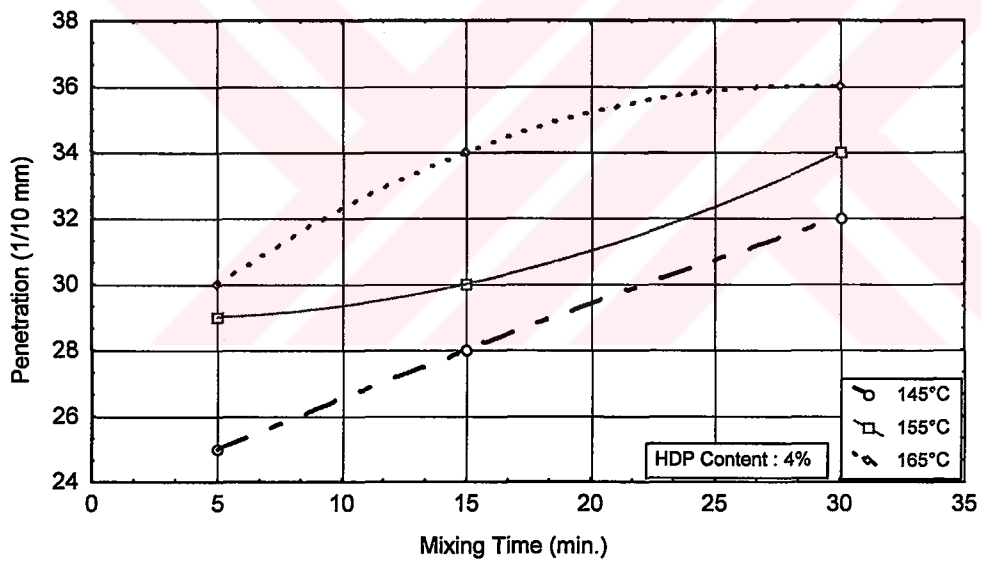


Figure 5.8 Penetration vs mixing time for 4% HDP content

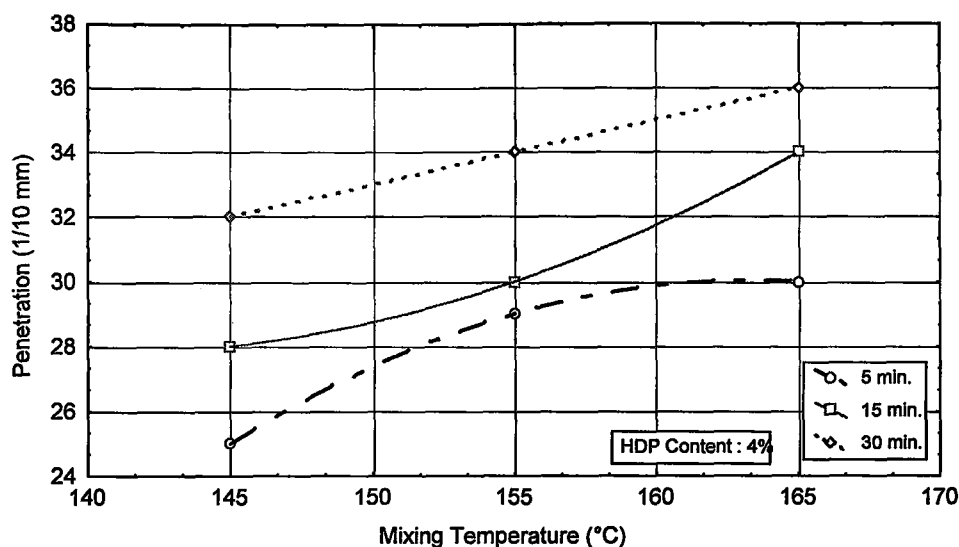


Figure 5.9 Penetration vs mixing temperature for 4% HDP content

Table 5.5 Penetration Test Results of HDP Modified Asfalts (1/10 mm)

Polyethylene Content (%)	Mixing Time , 5 min			Mixing Time , 15 min			Mixing Time , 30 min		
	Mixing Temperature (°C)			Mixing Temperature (°C)			Mixing Temperature (°C)		
	145	155	165	145	155	165	145	155	165
0	67	67	67	67	67	67	67	67	67
2	26	30	35	34	35	38	42	43	45
4	25	29	30	28	30	34	32	34	36
6	20	23	23	22	25	26	23	24	26
8	12	19	19	16	19	20	19	20	22

5.6.2 Softening Point

Bituminous binders do not exhibit a melting point but their consistency change gradually from the solid to liquid state by the application of heat. The amount of heat required to change the consistency of the binder depends on the chemical composition of the bitumen.

The softening point is a measure of a combination of viscosity, elastic properties, density, thermal conductivity and heat capacity, all of which can vary with temperature. In the ring and ball test, softening point of a binder is defined as the temperature at which a sample of binder contained in a brass ring; suspended in a water or glycerol bath, soften enough to allow a 9.55 mm. diameter steel ball of mass 3.5 grams, placed in the middle of sample, to fall through a height of 25 mm.

The effect of mixing time, mixing temperature and HDP concentration on the softening point test are given in Table 5.6 and also are presented graphically in Figures 5.10 to 5.17.

It is clear that the softening point of the mix increases with increasing HDP content. The softening point of the binder increases with decreasing mixing time and mixing temperature.

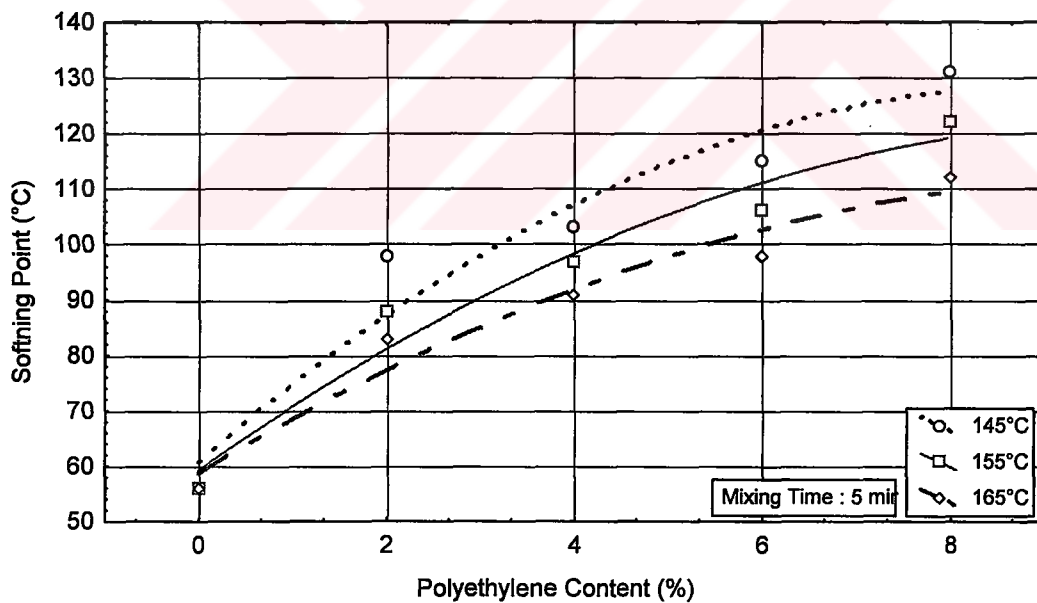


Figure 5.10 Softening point vs Polyethylene content for 5 min. mixing time

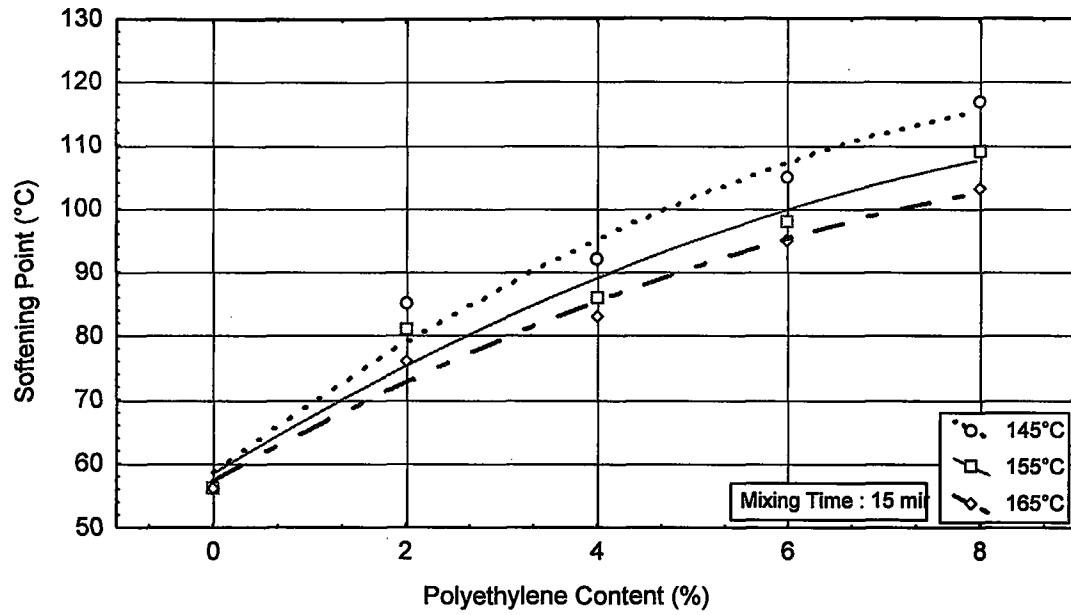


Figure 5.11 Softening point vs Polyethylene content for 15 min. mixing time

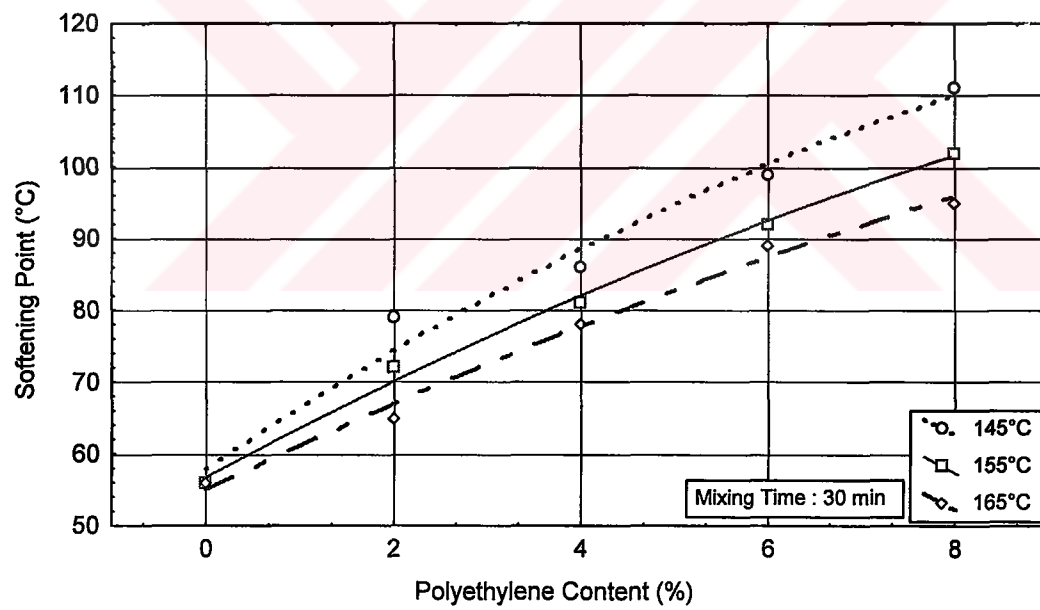


Figure 5.12 Softening point vs Polyethylene content for 30 min. mixing time

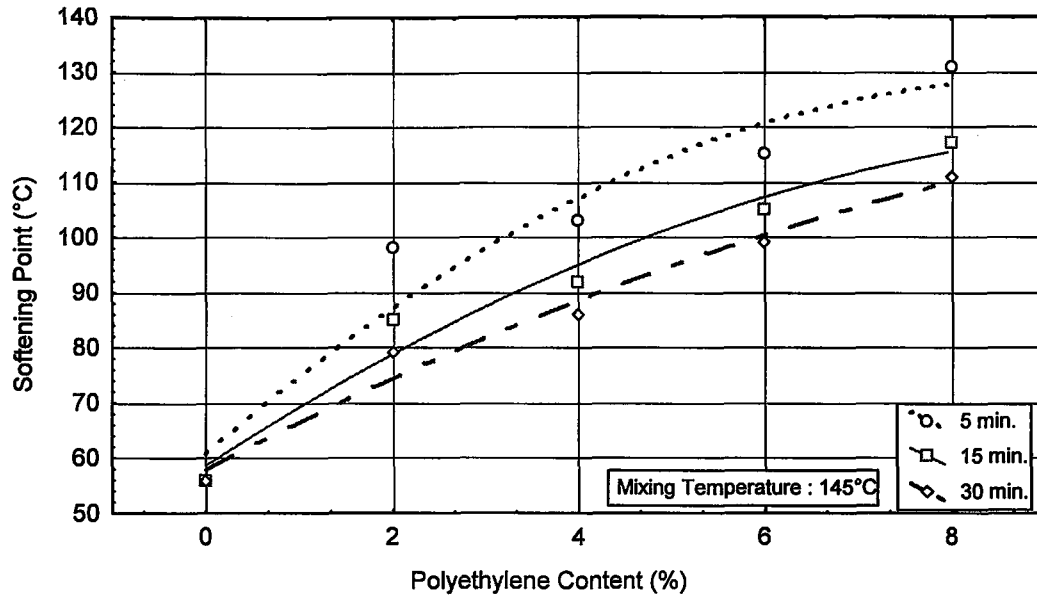


Figure 5.13 Softening point vs Polyethylene content for 145°C mixing temperature

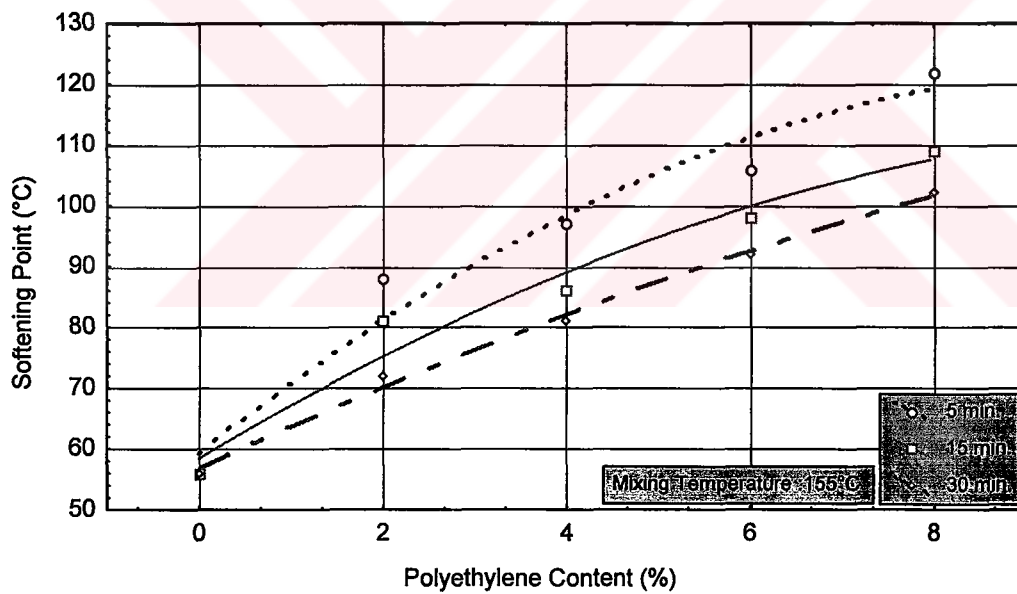


Figure 5.14 Softening point vs Polyethylene content for 155°C mixing temperature

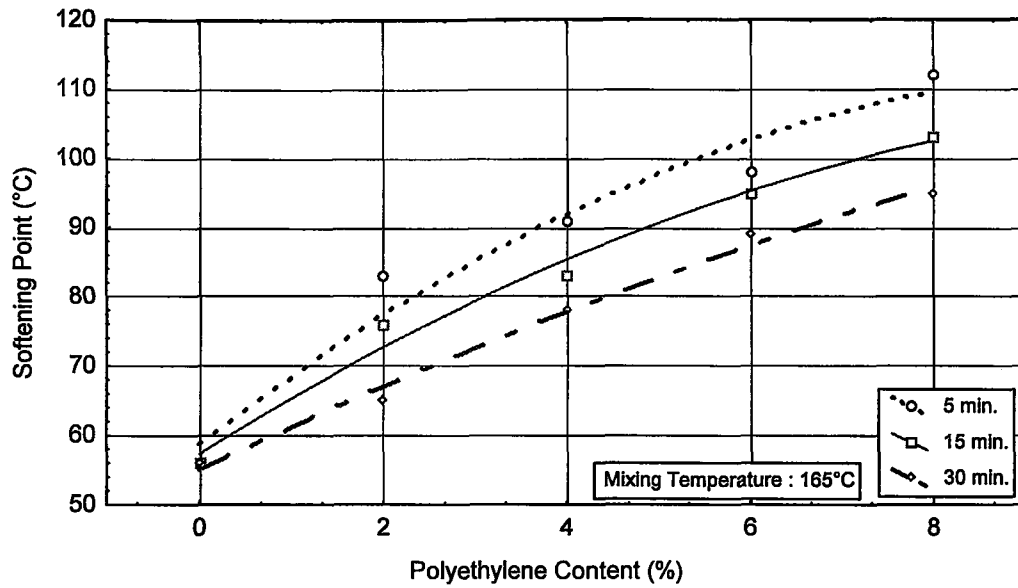


Figure 5.15 Softening point vs Polyethylene content for 165°C mixing temperature

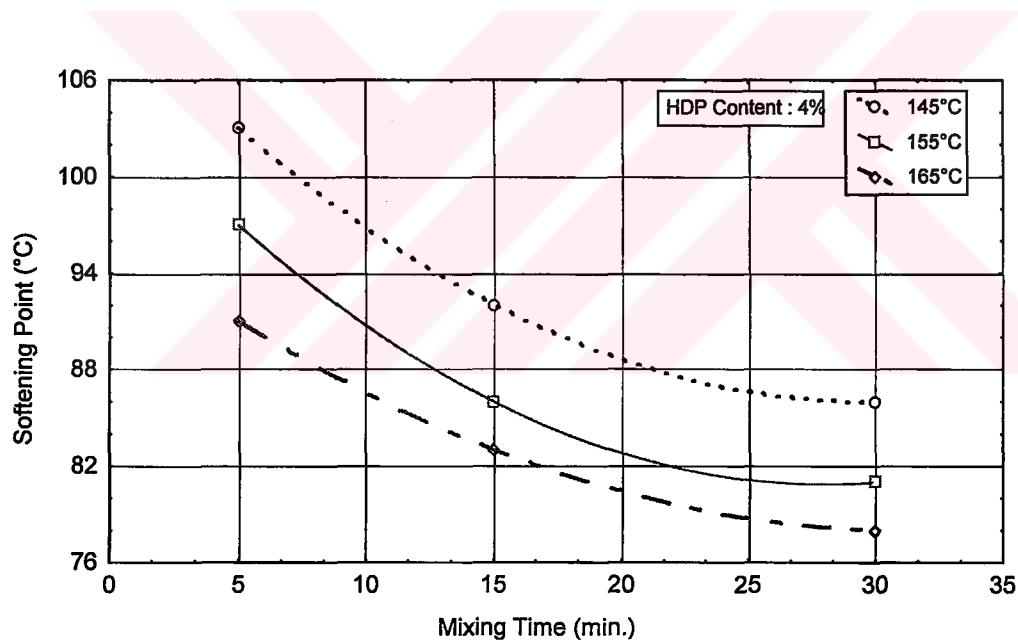


Figure 5.16 Softening Point vs mixing time for 4% HDP content

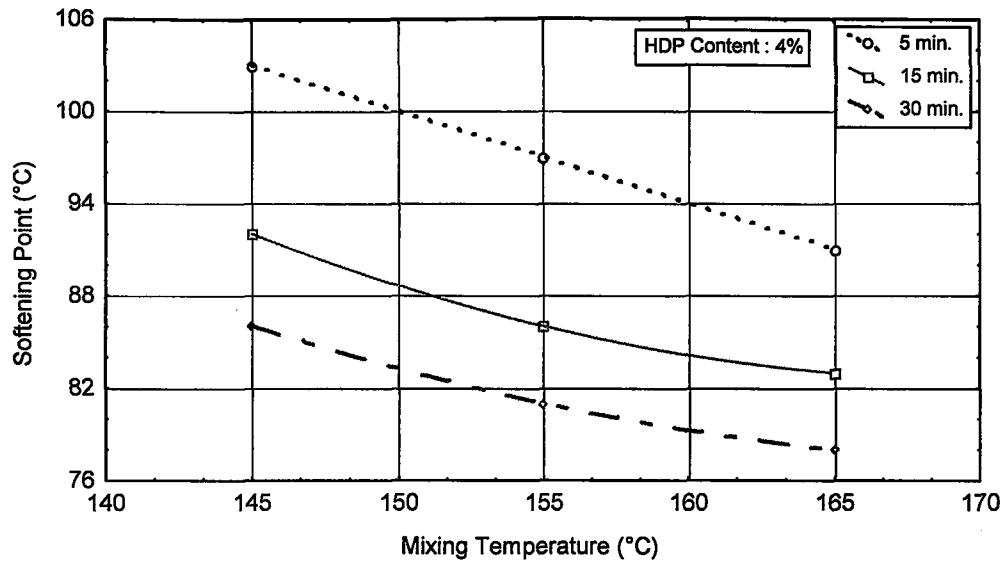


Figure 5.17 Softening point vs mixing temperature for 4% HDP content

Table 5.6 Softening Point Test Results of HDP Modified Asfalts (°C)

Polyethylene Content (%)	Mixing Time , 5 min			Mixing Time , 15 min			Mixing Time , 30 min		
	Mixing Temperature (°C)			Mixing Temperature (°C)			Mixing Temperature (°C)		
	145	155	165	145	155	165	145	155	165
0	56	56	56	56	56	56	56	56	56
2	98	88	83	85	81	76	79	72	65
4	103	97	91	92	86	83	86	81	78
6	115	106	98	105	98	95	99	92	89
8	131	122	112	117	109	103	111	102	95

5.6.3 Ductility

The results obtained from the ductility tests are presented in Figure 5.18 to 5.25. The results of the ductility tests are given in Table 5.7. The results clearly show that the hardness of the binder increased with decreasing mixing time and mixing temperature. As the percentage of HDP increased the ductility values decreased.

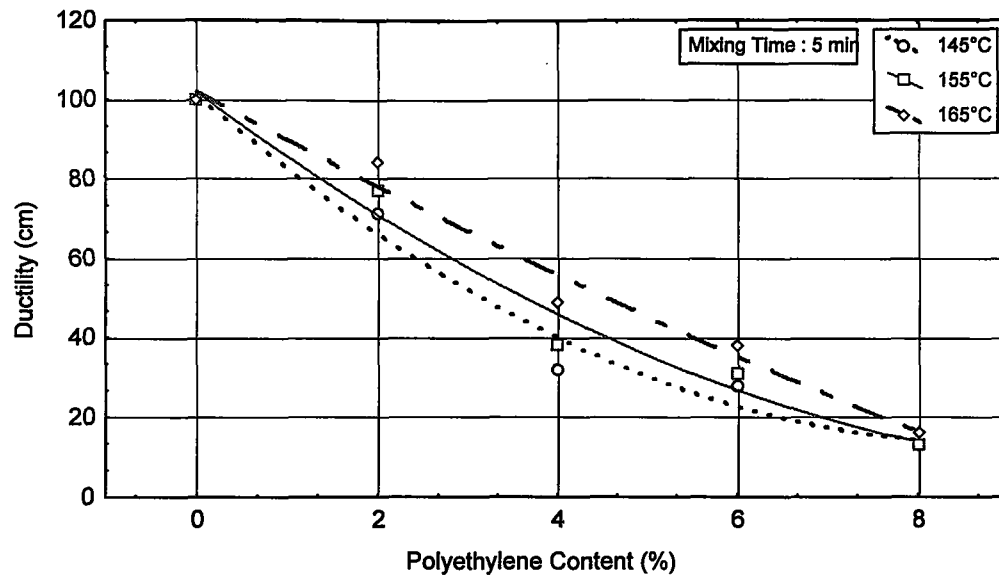


Figure 5.18 Ductility vs Polyethylene content for 5 min mixing time

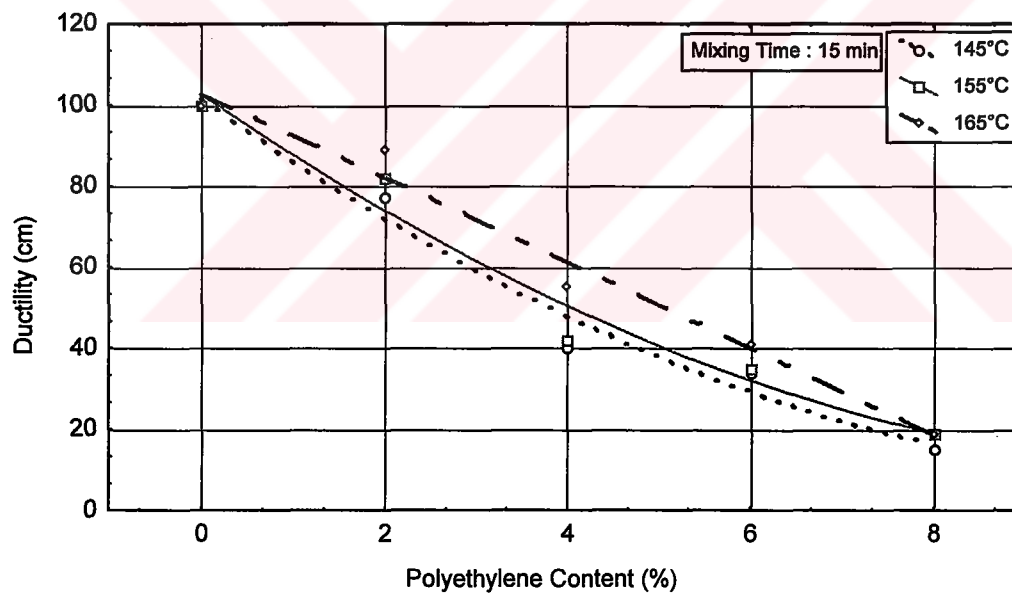


Figure 5.19 Ductility vs Polyethylene content for 15 min mixing time

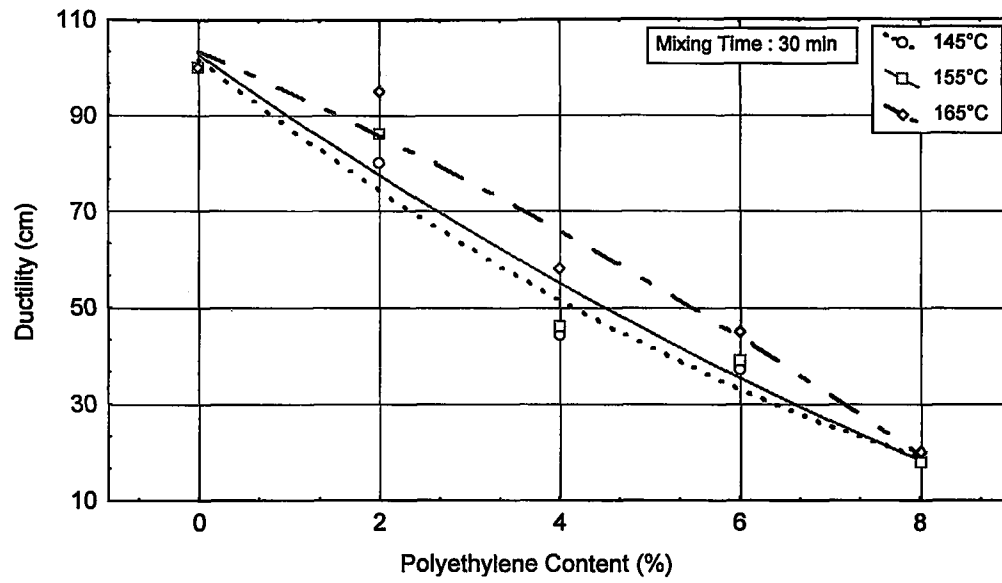


Figure 5.20 Ductility vs Polyethylene content for 30 min mixing time

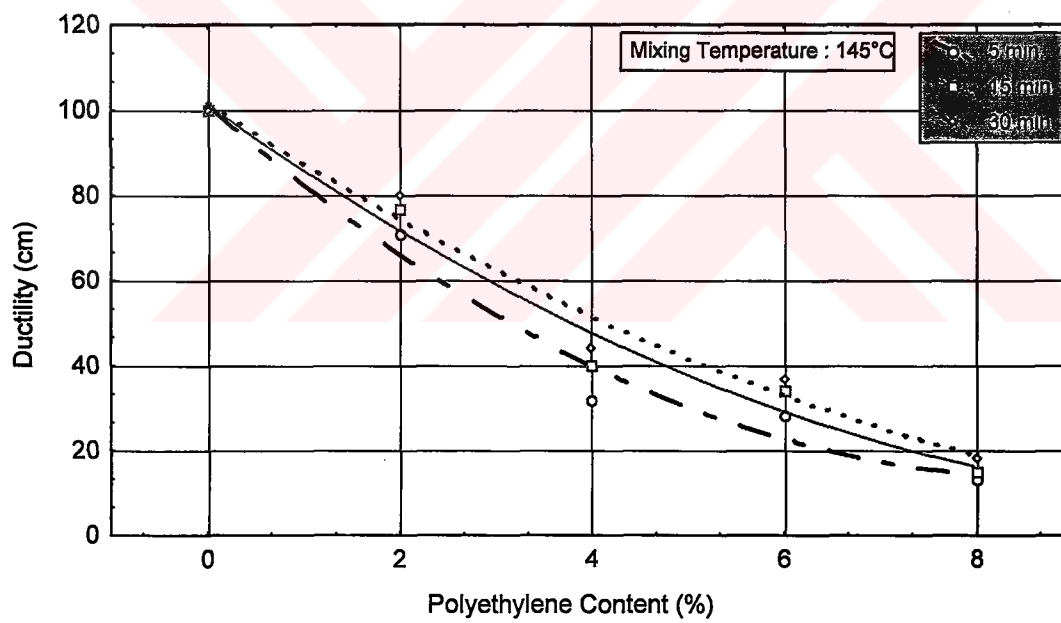


Figure 5.21 Ductility vs Polyethylene content for 145°C mixing temperature

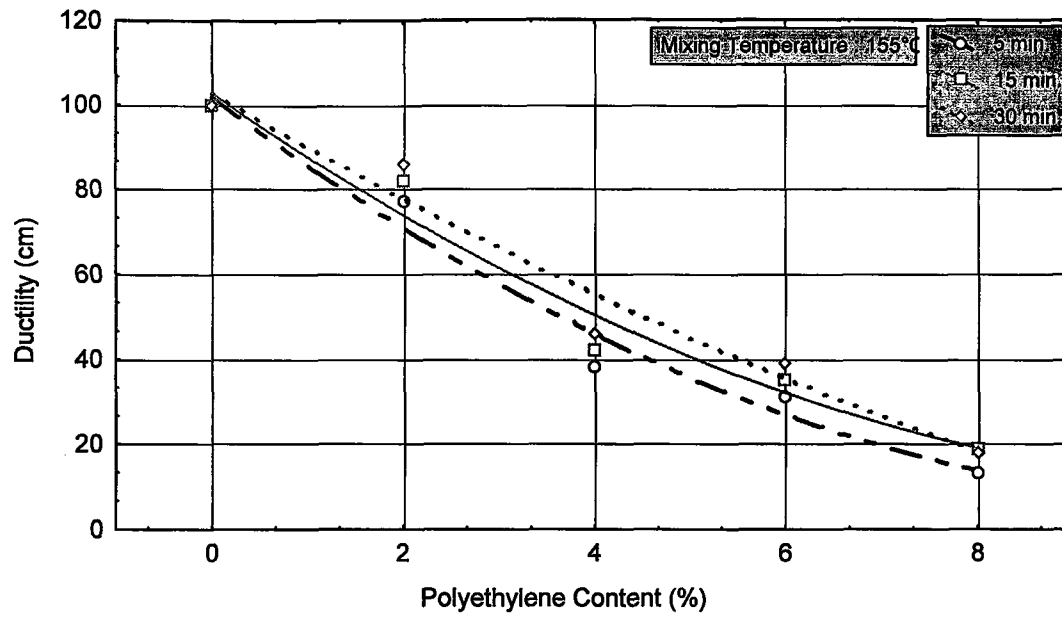


Figure 5.22 Ductility vs Polyethylene content for 155°C mixing temperature

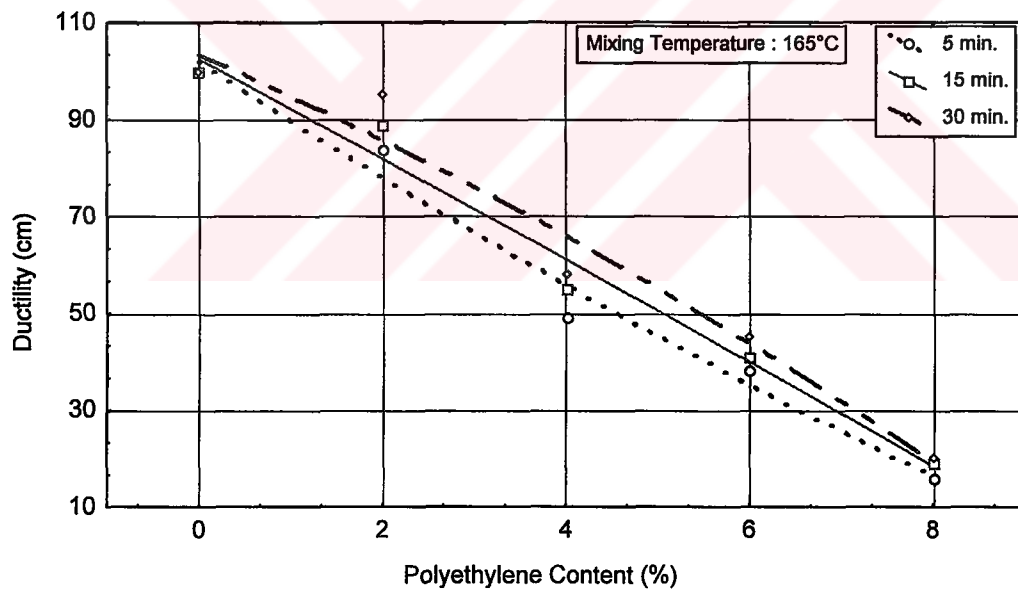


Figure 5.23 Ductility vs Polyethylene content for 165°C mixing temperature

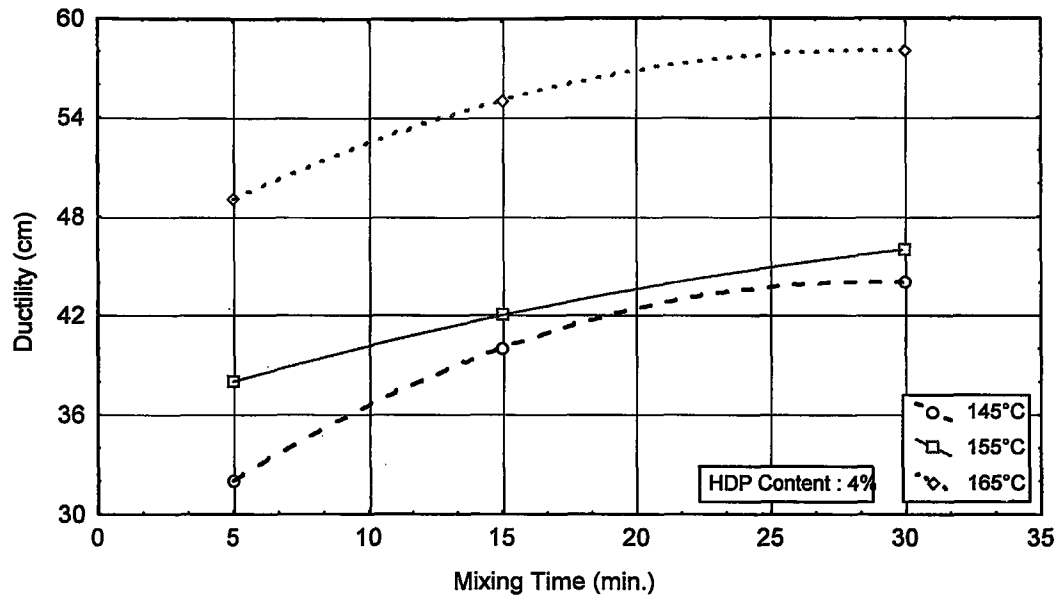


Figure 5.24 Ductility vs mixing time for 4% HDP content

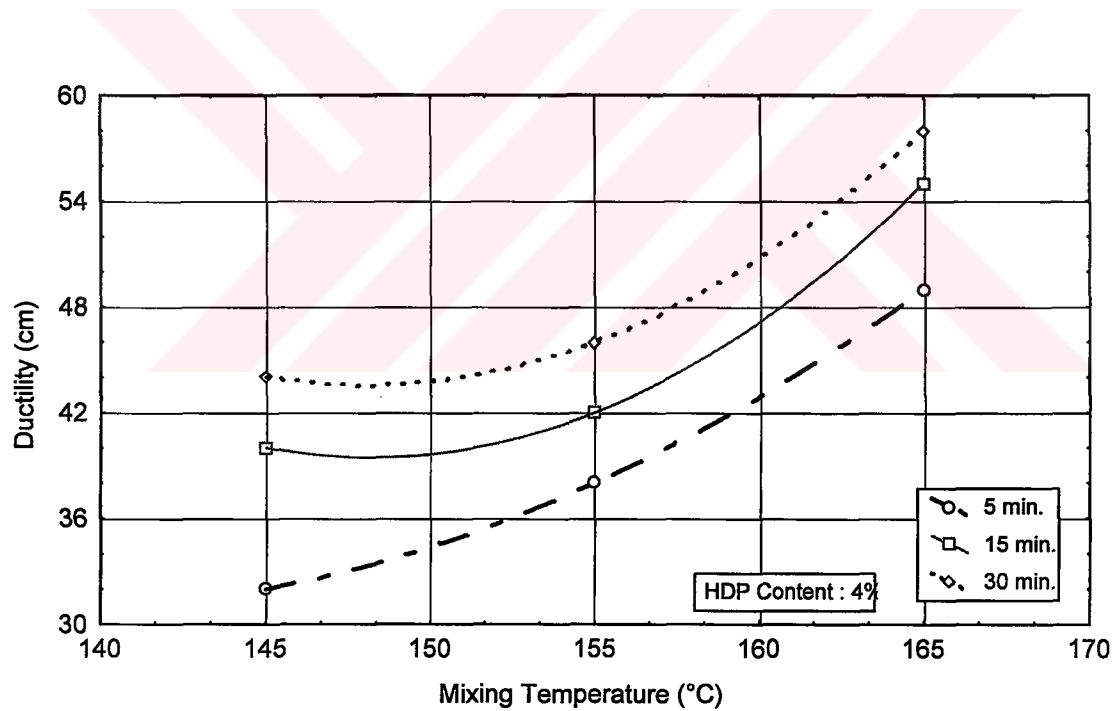


Figure 5.25 Ductility vs mixing temperature for 4% HDP content

Table 5.7 Ductility Test Results of HDP Modified Asfalts (cm)

Polyethylene Content (%)	Mixing Time , 5 min			Mixing Time , 15 min			Mixing Time , 30 min		
	Mixing Temperature (°C)			Mixing Temperature (°C)			Mixing Temperature (°C)		
	145	155	165	145	155	165	145	155	165
0	100+	100+	100+	100+	100+	100+	100+	100+	100+
2	71	77	84	77	82	89	80	86	95
4	32	38	49	40	42	55	44	46	58
6	28	31	38	34	35	41	37	39	45
8	13	13	16	15	19	19	18	18	20

5.6.4 The Calculation of Viscosity

In this investigation, the viscosity of HDP modified bitumen was calculated using equation 2.6 and 2.7.

The effect of mixing time, mixing temperature and HDP concentration on the viscosity of HDP modified bitumen specimens are given in Table 5.8 and also are presented graphically in Figure 5.26 to 5.33.

It is clear that the viscosity of the mix increased with increasing HDP content. The viscosity of the binder increased with decreasing mixing time and mixing temperature.

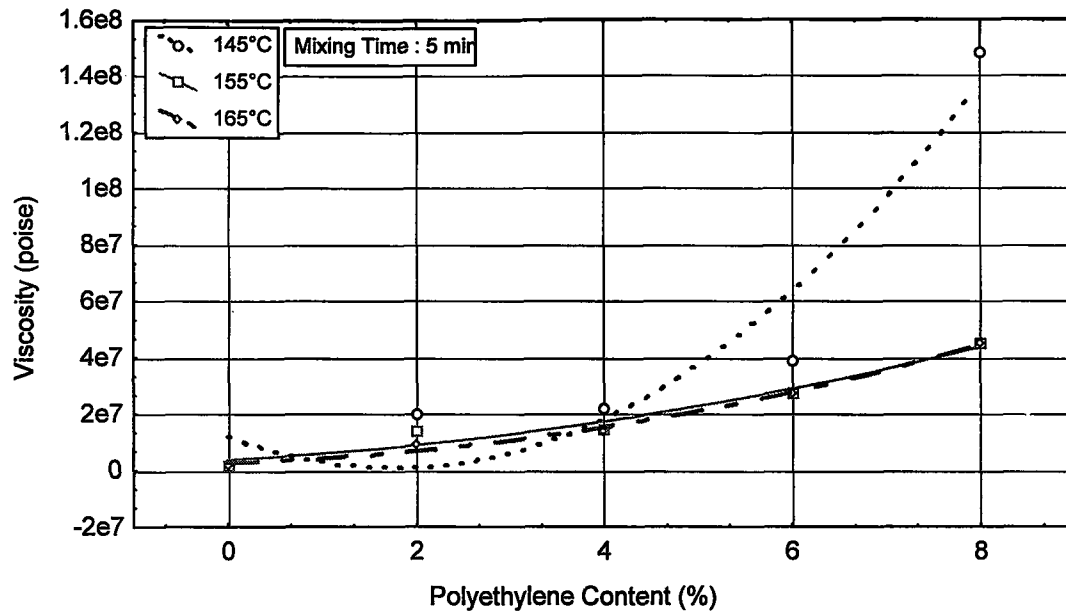


Figure 5.26 Viscosity vs Polyethylene content for 5 min. mixing time

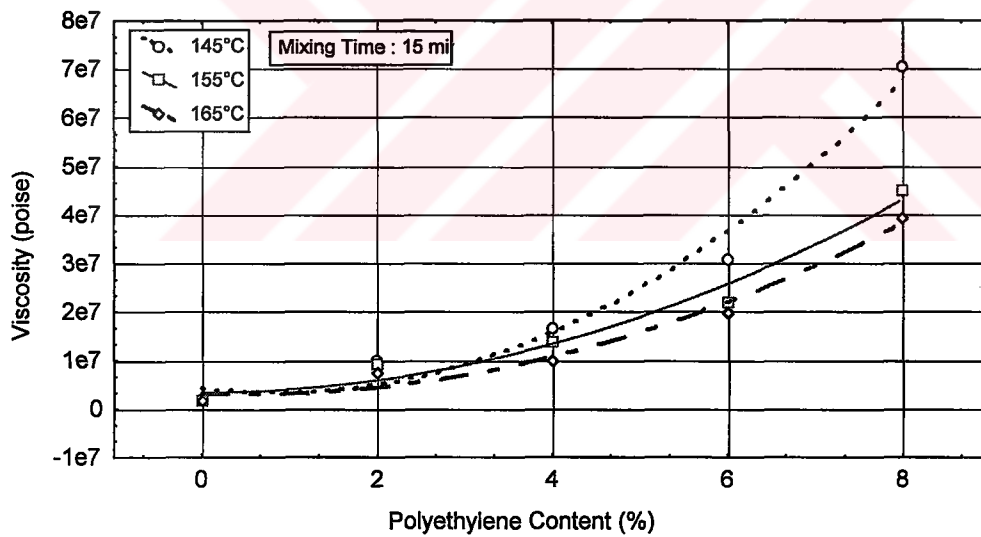


Figure 5.27 Viscosity vs Polyethylene content for 15 min. mixing time

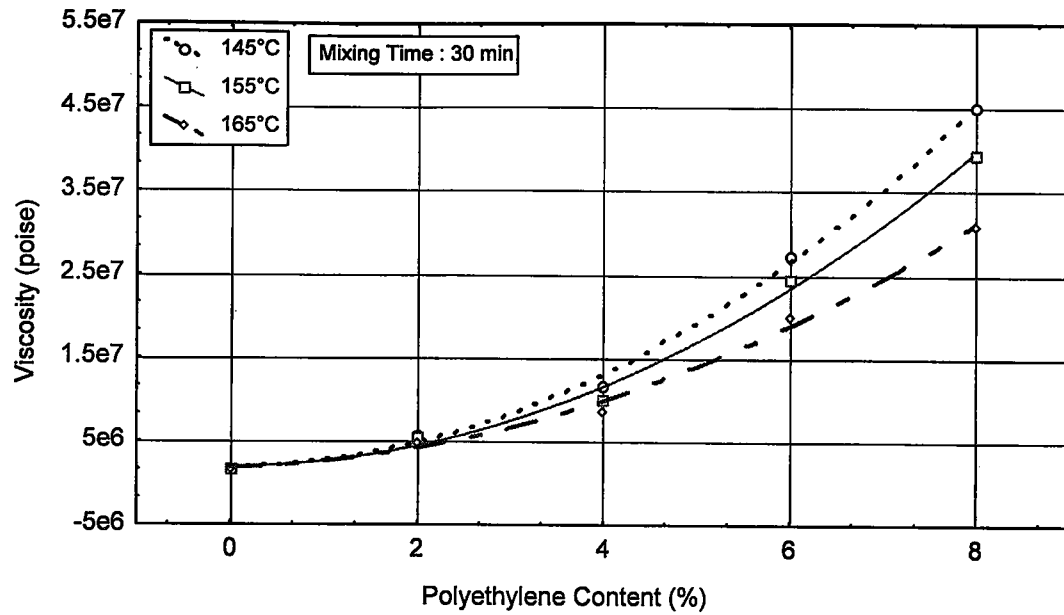


Figure 5.28 Viscosity vs. Polyethylene content for 30 min. mixing time

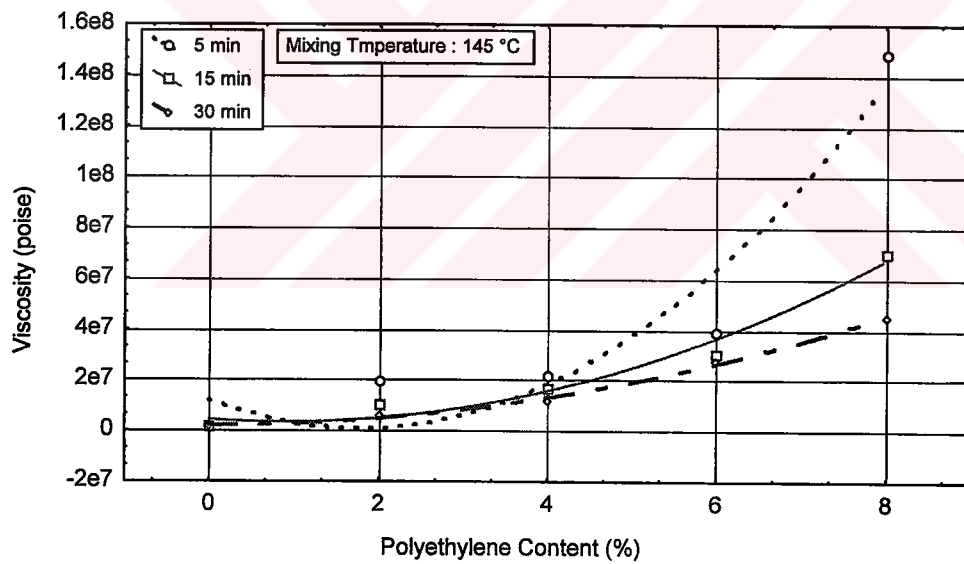


Figure 5.29 Viscosity vs Polyethylene content for 145°C mixing temperature

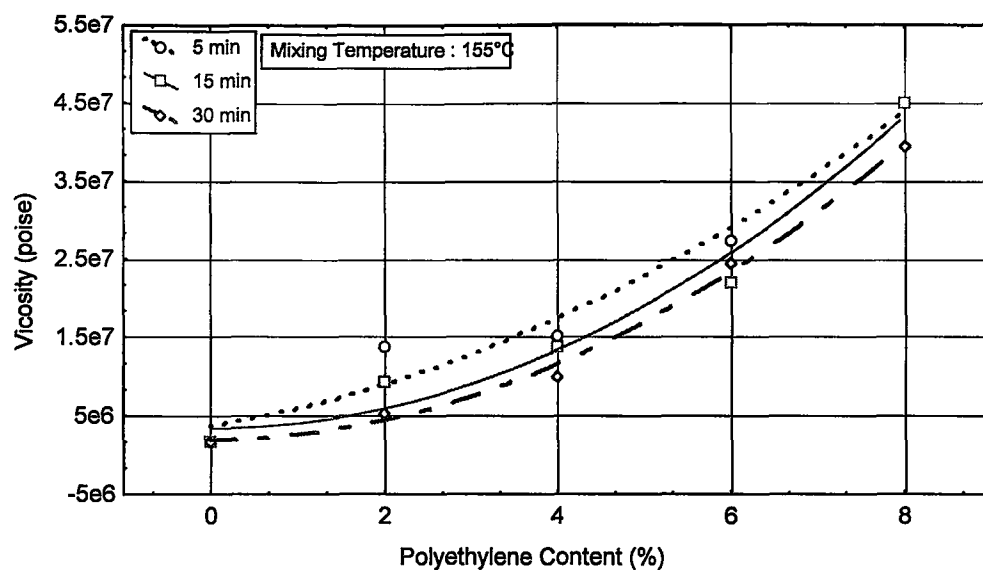


Figure 5.30 Viscosity vs Polyethylene content for 155°C mixing temperature

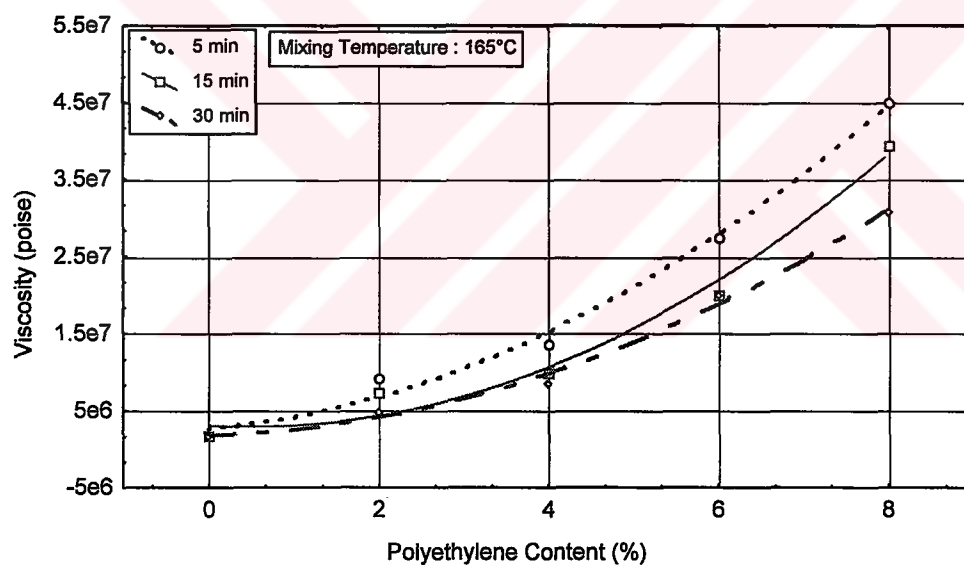


Figure 5.31 Viscosity vs Polyethylene content for 165°C mixing temperature

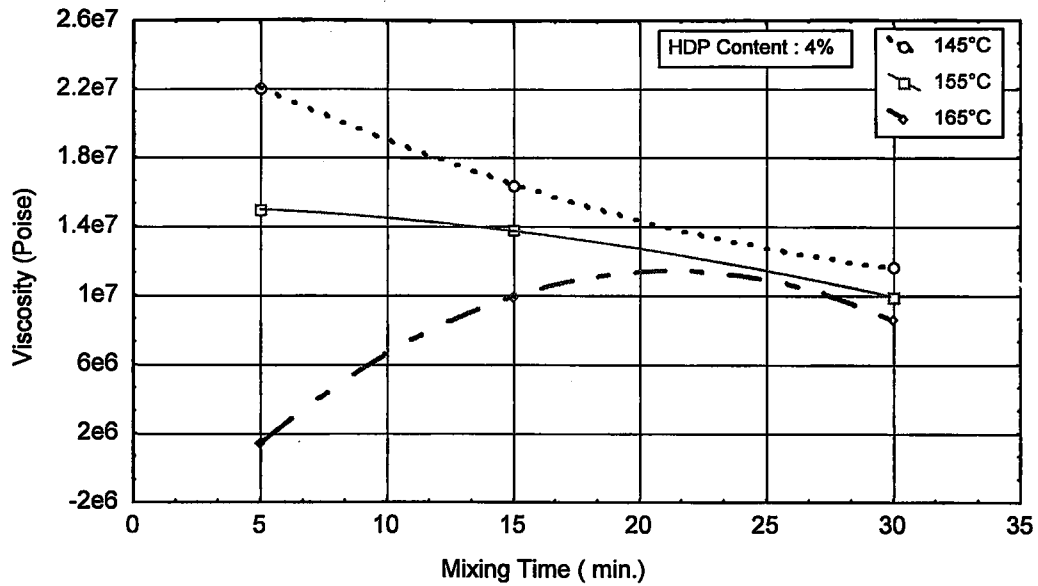


Figure 5.32 Viscosity vs mixing time for 4% HDP content

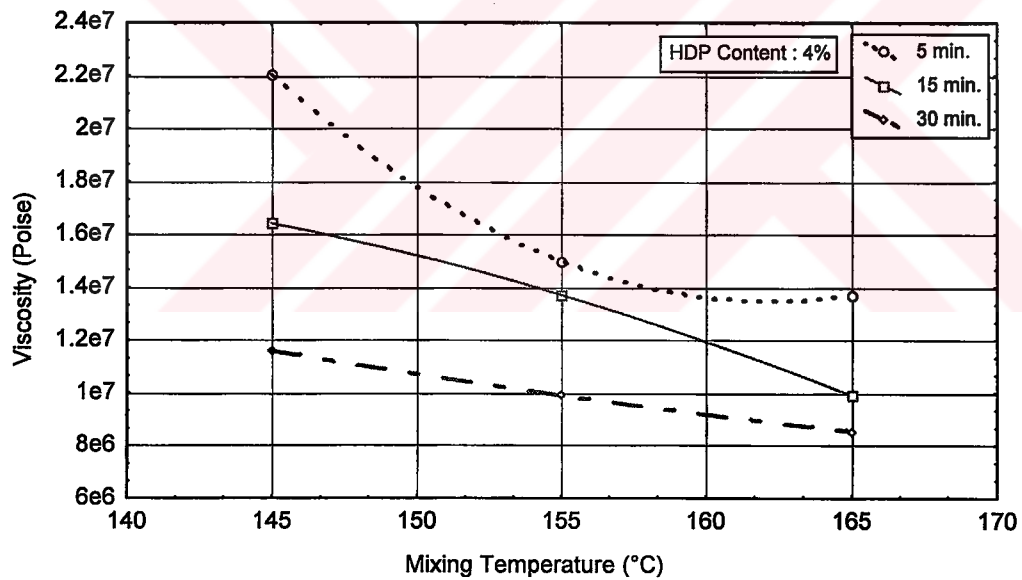


Figure 5.33 Viscosity vs mixing temperature for 4% HDP content

Table 5.8 The Results of Viscosity Calculations at 25°C of HDP Modified Asphalts

Polyethylene Content (%)	Mixing Time , 5 min			Mixing Time , 15 min			Mixing Time , 30 min		
	Mixing Temperature (°C)			Mixing Temperature (°C)			Mixing Temperature (°C)		
	145	155	165	145	155	165	145	155	165
0	1,7E+06	1,7E+06	1,7E+06	1,7E+06	1,7E+06	1,7E+06	1,7E+06	1,7E+06	1,7E+06
2	19897243	13715396	9186428	9905546	9186428	7417990	5718412	5379050	4779375
4	22033302	14979207	13715396	16410157	13715396	9905546	11596680	9905546	8537626
6	39359141	27367255	27367255	30720242	22033302	19897243	27367255	24500468	19897243
8	149000000	44974282	44974282	70309118	44974282	4E+07	44974282	39359141	30720242

5.7 RESISTANCE OF BITUMINOUS MIXTURES PREPARED WITH HDP MODIFIED BINDER TO PLASTIC FLOW

The Marshall Test Method was used for determining the resistance to plastic flow of bituminous mixtures prepared with HDP modified binder.

5.7.1 Preparation of Test Specimens

The Marshall specimens (four inches in diameter by two and one-half inches in height), were fabricated in accordance with ASTM D 1559 [66]. In preparing the Marshall specimens, care was exercised to ensure that the specimens did not have significant surface irregularities that might interfere with the proper contact between the specimen and the loading strip. The steps in preparation and compaction of mixture are described below.

- The aggregate fraction for the selected gradation and the desired quantities were combined. To ensure a hot and dry mix, the aggregate was placed in a forced-draft oven at the selected temperature (160°C), 10°C above the mixing temperature, for at least six hours, while the binder was heated in open beakers to specific temperatures on electric hot plates at constant stirring to avoid spot overheating.

- The heated aggregate was placed in a mixing bowl preheated to the same temperature as the aggregate; then the bowl was placed on a balance where the appropriate amount of binder was added.
- The binder was spread over the aggregate with a preheated spoon and then mixed with a mechanical mixer using a wire beater. The binder and the aggregate were mixed for about two minutes to achieve a uniform distribution of binder throughout.
- A standart Marshall mold assembly (mold, plate and collar) was preheated in the oven to 170°C and then placed on the compaction pedestal in the mold. Eighty five blows were applied on each side of the specimen using the mechanically operated Marshall Compactor.
- After compaction was accomplished, the specimens were allowed to cool to a temperature that no deformation would result when removing them from the mold. The specimens were removed form the mold by means of an extrusion jack.
- After the specimens cooled to room temperature, the bulk specific gravity was determined by the water displacement method, which specifies that the air dry weight, the weight in water and the saturated surface dry weight be mesured and used in the calculation, according to ASTM D 2726-83 test procedure.
- The height of the test specimens, which is important in determining the Marshall Stability, was measured by the use of a Vernier caliper. The specimen height was measured at three different positions and the average was taken as the height of the specimen. If variation in height were significant, the specimen was discarded.

In the first Marshall test, the asphalt cement percentages used were 2.5 - 3 - 3.5 - 4 - 4.5 - 5 - 5.5 - 6 - 6.5 and 7. First, The Marshall specimens were prepared with 60/70 penetration grade asphalt according to the above procedure and the stability and flow tests were performed as follows :

The specimens were then placed in the breaking head and the transducer for measuring the flow was adjusted. The load was applied to the specimen by means of the testing machine head which advances at a constant rate of 2 inches (51 mm) per minute, until the maximum value was reached. After the Marshall test device stoped automatically ,the stability and the flow values were recorded. After the completion

of the stability and flow tests, density and void analysis were made for each series of test specimens as follows :

- Average unit weights for each asphalt content is determined, and unit weight versus asphalt content curve was plotted graphically.
- Using the apparent specific gravity of coarse aggregate, fine aggregate, filler and AC in the mix, percent air voids in the total mix was computed.
- Using the same specific gravity values, percent aggregate voids filled with asphalt was computed.

Marshall Stiffness was calculated according to the equation 5.2

$$S_{\text{marshall}} = 15.69 P/F \quad (5.2)$$

where,

S_{marshall} : Marshall Stiffness(MPa)

P : Marshall Stability (N)

F : Flow (mm)

The results for determining the optimum asphalt cement content were presented in Figure 5.35 to 5.39.

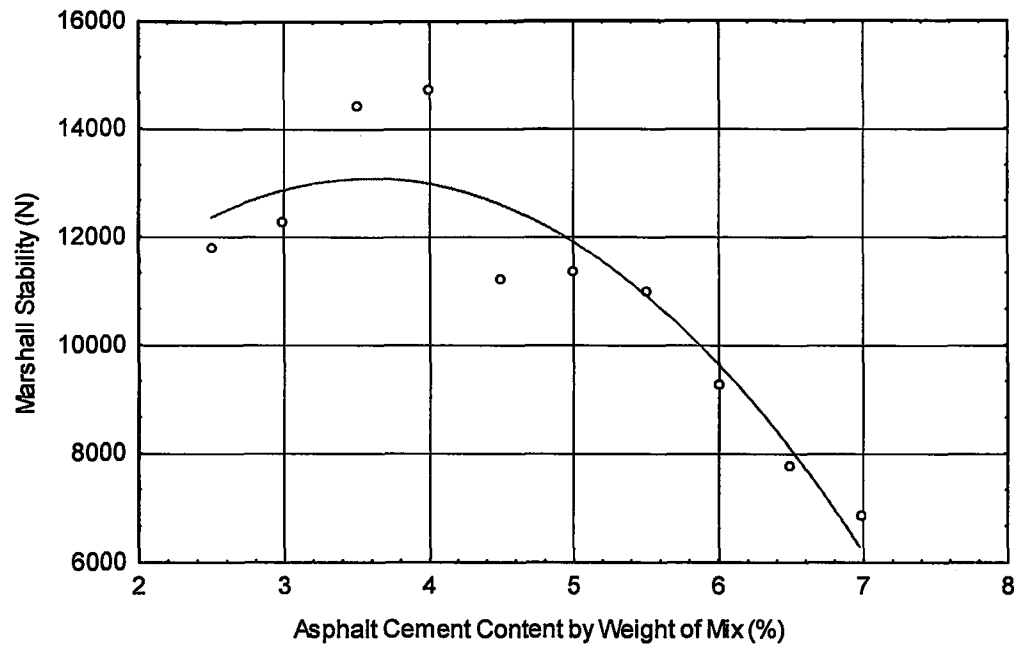


Figure 5.34 Marshall stability vs Asphalt Cement Content

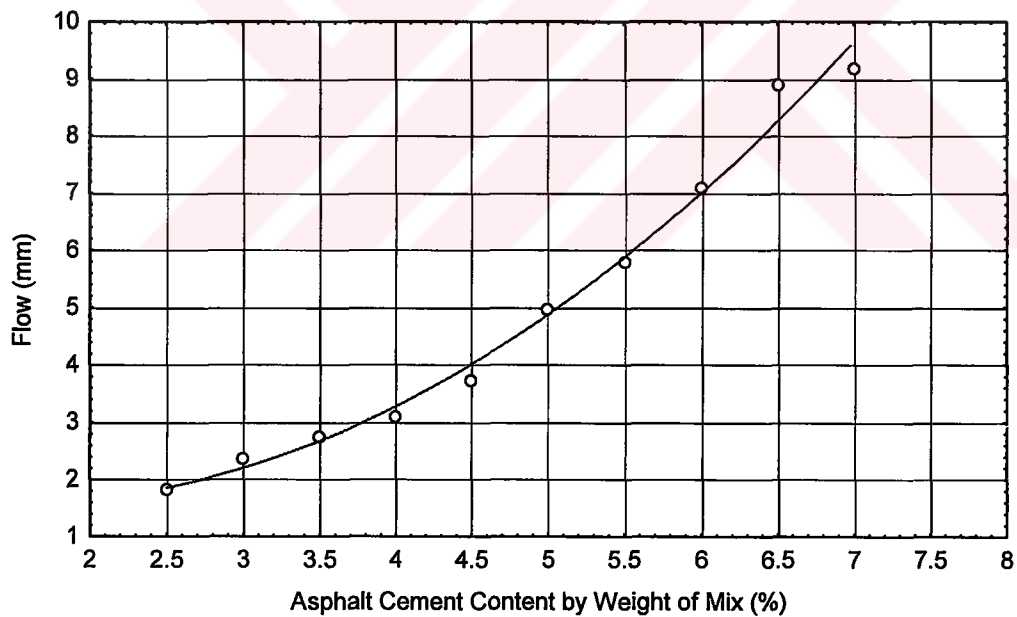


Figure 5.35 Flow vs Asphalt Cement Content

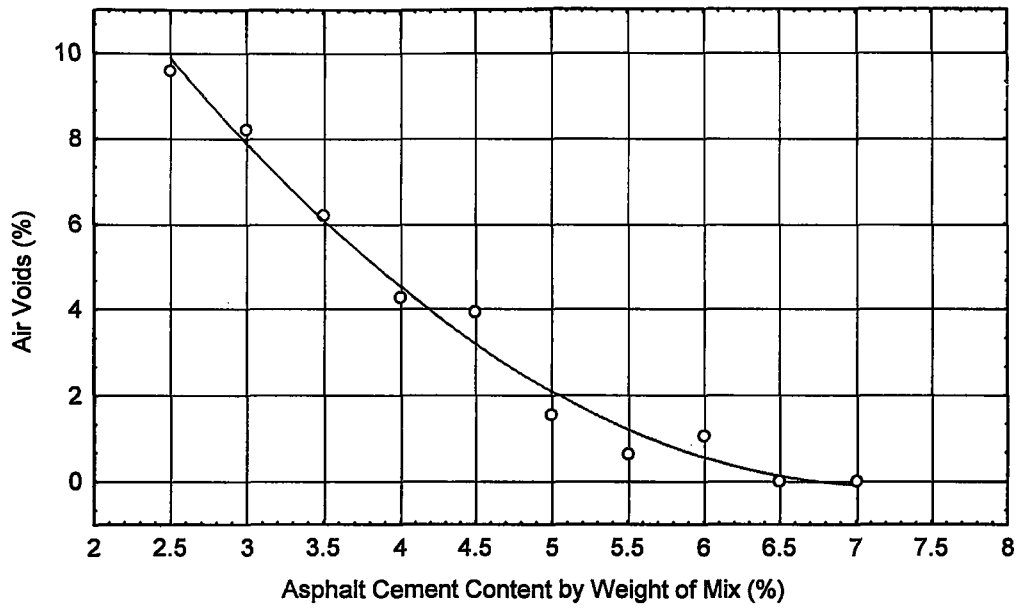


Figure 5.36 Air voids vs Asphalt Cement Content

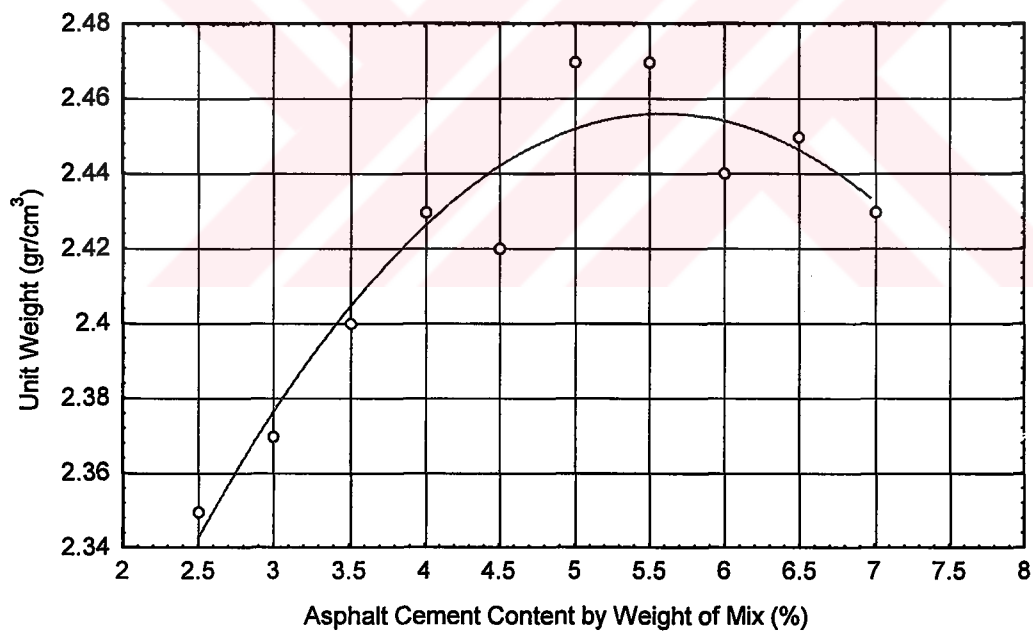


Figure 5.37 Unit weight vs Asphalt Cement Content

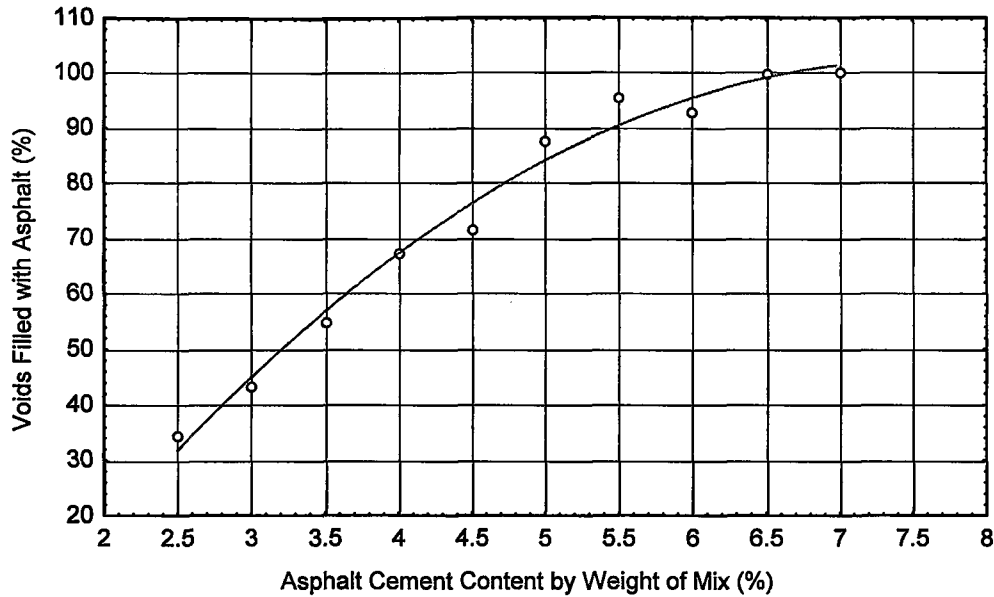


Figure 5.38 Voids Filled with Asphalt Cement Content

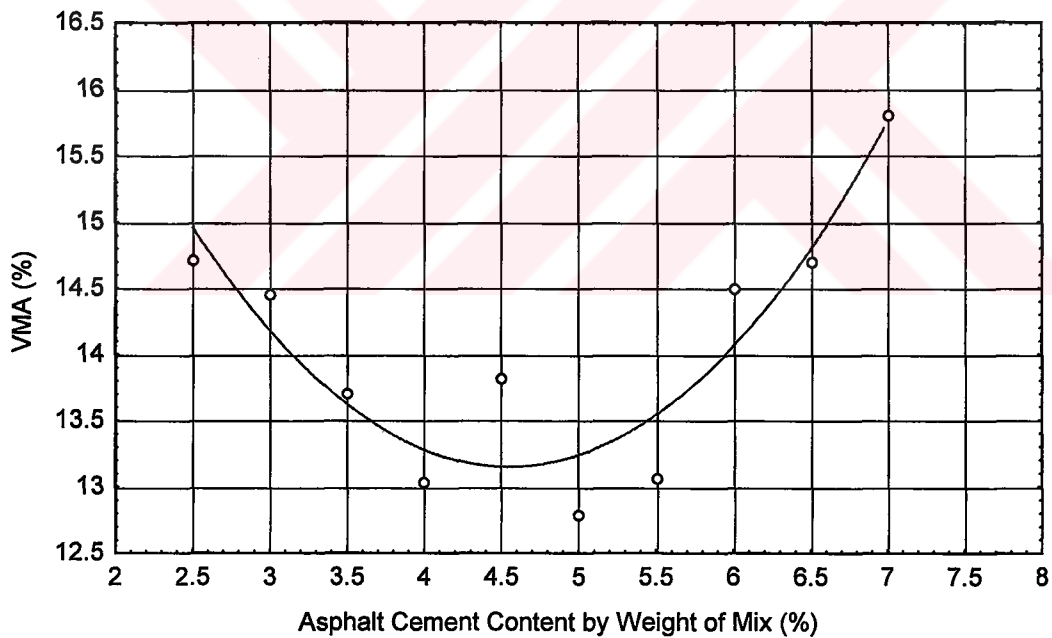


Figure 5.39 VMA vs Asphalt Cement Content

Optimum asphalt cement content was determined as follows :

The asphalt cement content for maximum unit weight : 5.5 %

The asphalt cement content for 4 % air voids : 4.2 %

The asphalt cement content for 80 % voids of filled with bitumen : 4.7 %

The asphalt cement content for maximum stability (13350 N) : 3.6 %

The optimum asphalt cement content is the average of these values that is 4.5 percent of the total mix. It is seen from the graphics that 4.5 % asphalt cement content provides the criterion in the specification (Table 5.9). This content was checked with regard to the flow value.

Table 5.9 Specification of General Directorate of Turkish Highway for Surface Coarse Subjected to High Volume of Traffic

	Specification Limits
Stability (kg)	min 9000 N (900 kg)
Air Voids (%)	3-5
Flow (mm)	2-4
Voids of filled with Asphalt Cement (%)	75-85

After determining the optimum asphalt cement content (4.5%), Marshall tests were performed on the specimens which contained a binder obtained by mixing HDP in powder form at percentages 2-4-6 and 8 by weight of asphalt cement, the asphalt cement being prepared at the specific conditions such as 145-155-165°C mixing temperature and 5-15-30 minute mixing time.

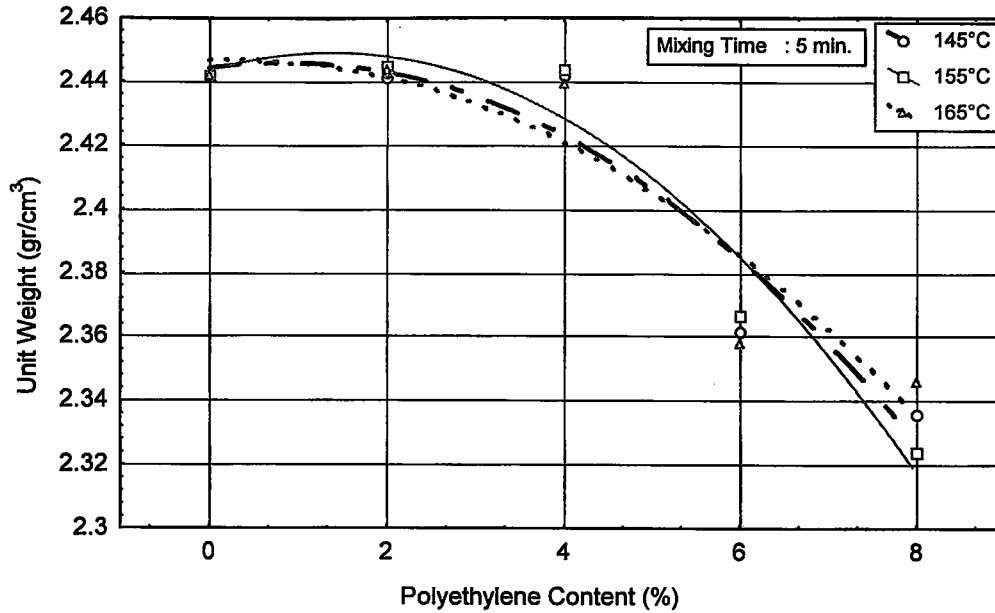


Figure 5.40 Unit weight vs polyethylene content for 5 min. mixing time

The graph shows the variation of unit weight with HDP content and mixing temperature, the mixing time being 5 min. The maximum unit weight is reached at 155°C temperature with 2% HDP. At 165°C mixing temperature ; the unit weight decreases with increasing HDP content. Thus, 2% HDP and 155°C mixing temperature can be considered to be the optimum for min mixing time. The maximum value of unit weight was about 2.5 gr/cm³.

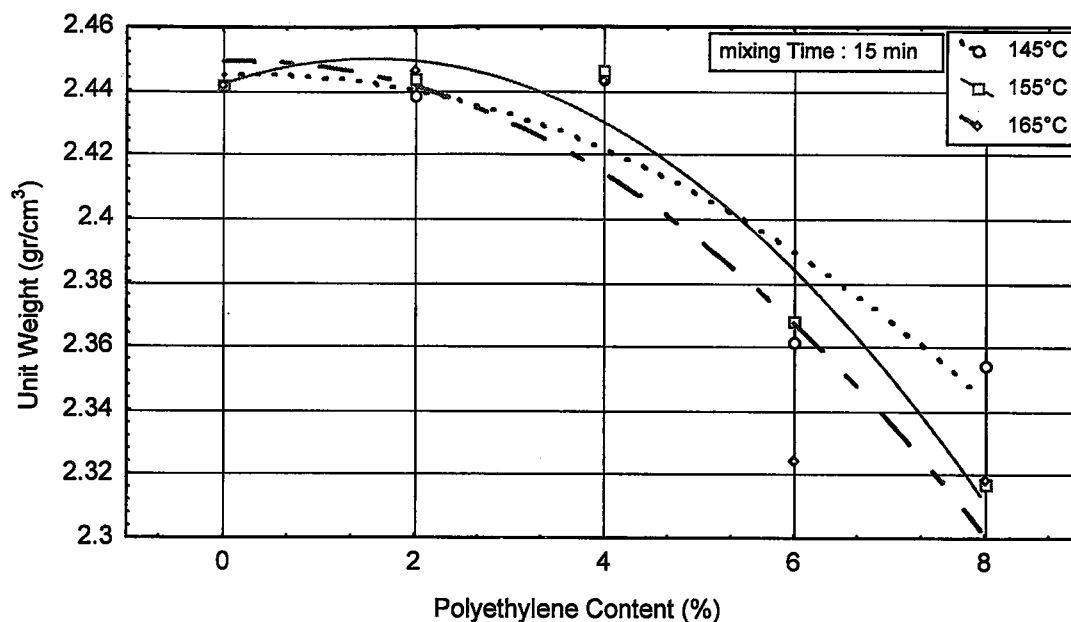


Figure 5.41 Unit weight vs polyethylene content for 15 min. mixing time

With 15 minute mixing time, the differences are more emphasized. At 145°C and 165°C mix. temperatures the maximum unit weights are obtained with 0% HDP, and with increasing HDP content unit weight decreases steadily. The 155°C mixing time curve, as opposed to the other two, has a maximum at 2% HDP. This result is in conformity with the result obtained from 5 min. mixing. The maximum value of unit weight is again about 2.5 gr/cm³.

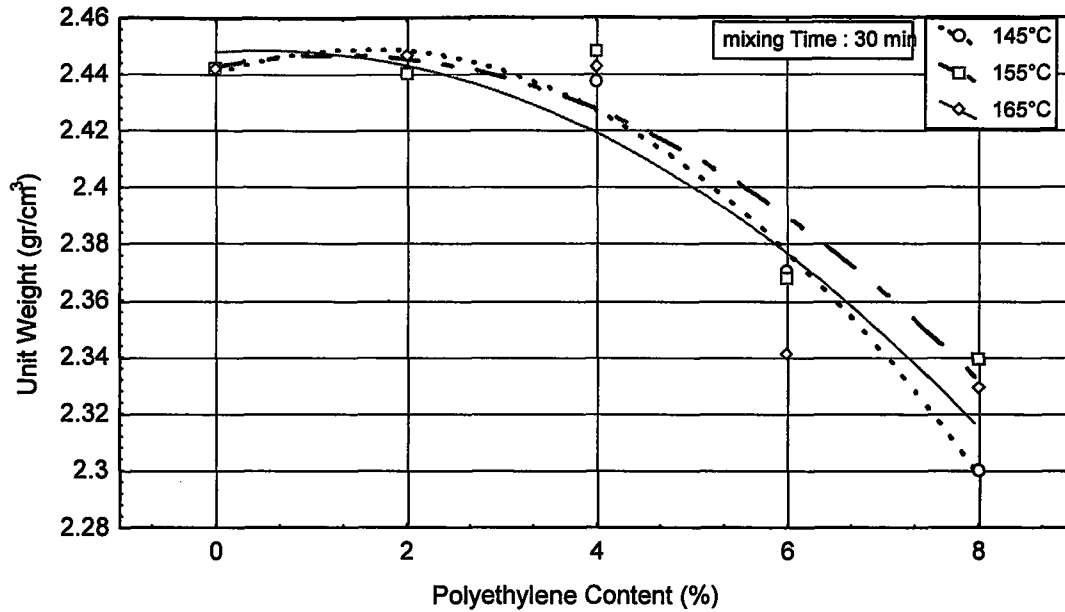


Figure 5.42 Unit weight vs polyethylene content for 30 min. mixing time

30 min. mixing time has brought an improvement in 145°C curve which is reasonable, because longer mixing time can provide better mixing of HDP and asphalt cement. The curves for 145°C and 155°C have a common optimum at 1.8% HDP, but the maximum unit weight for 155°C mixing temperature is even lower than the value obtained from 15 min. mixing time. This may result from a minor segregation in the asphalt cement mix at longer mixing times. The behavior of 165°C curve seems insensitive to the mixing time. As a result, 165°C mix temperature is not suitable for HDP treatment, probable choices are 15 min mixing at 155°C with 2% HDP or 30 min at 145°C with 1.8% HDP.

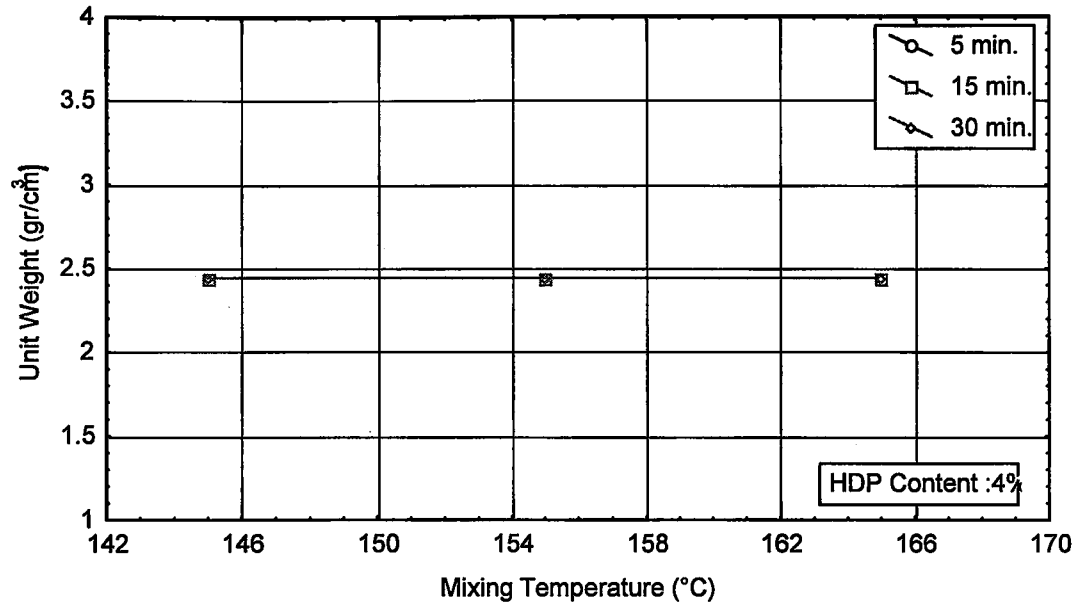


Figure 5.43 Unit weight vs mixing temperature for 4% HDP content

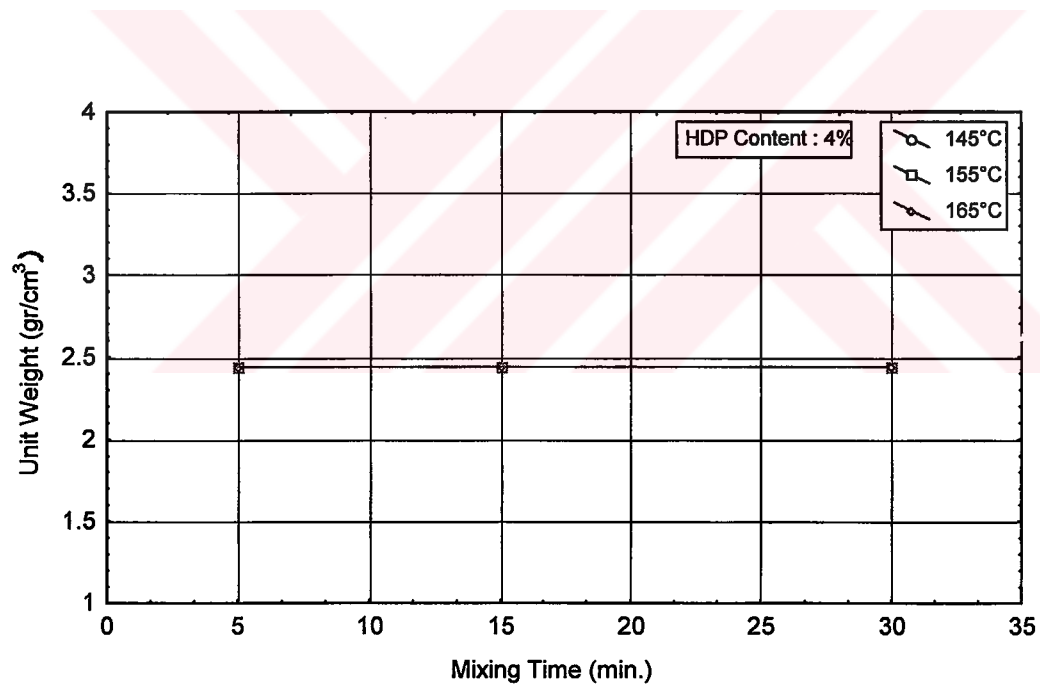


Figure 5.44 Unit weight vs. mixing time for 4% HDP content

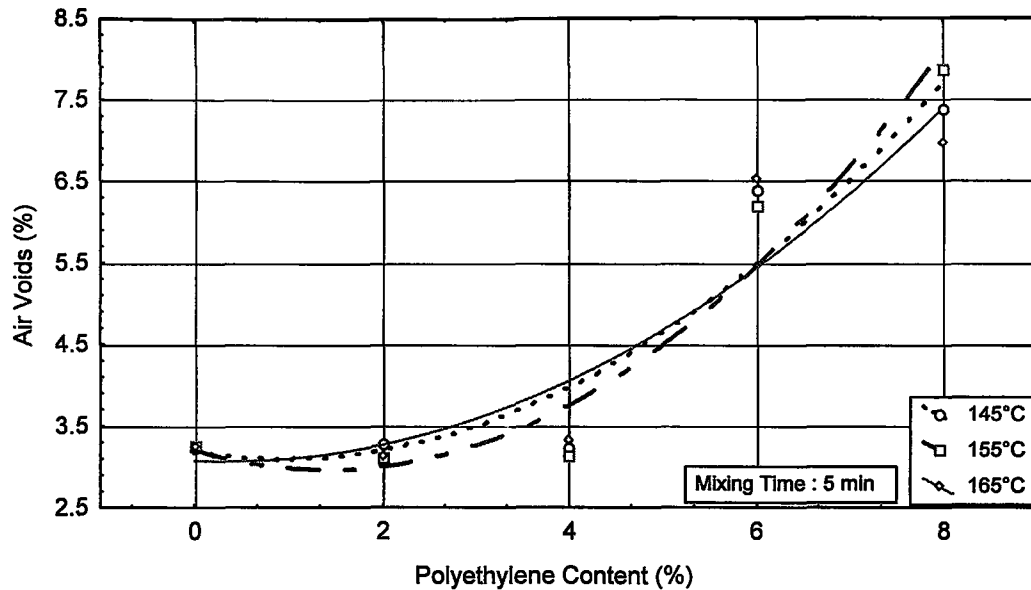


Figure 5.45 Air voids vs polyethylene content for 5 min. mixing time

This graph depicts the variation of air voids with HDP content and mixing temperature. Three mixing temperatures has been chosen 145,155,165°C. The percent air voids is almost constant between 0-2% HDP for all three mixing temperatures and increases parabolically with higher HDP contents. The curve corresponding to 155°C mixing makes a slight minimum at 2% HDP yet the value is about 3% which is acceptable.

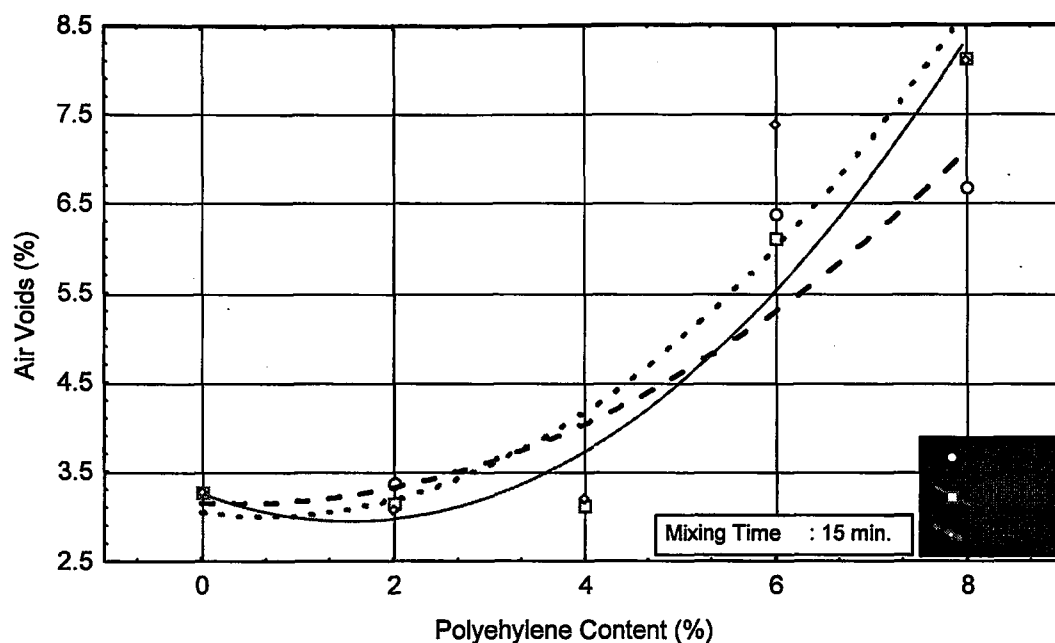


Figure 5.46 Unit weight vs polyethylene content for 15 min. mixing time

The air voids percentage for 145°C and 165°C mixing temperature increases parabolically with HDP content. The drop in air voids at 155°C mixing is more emphasized for this mixing time but it is still around acceptable lower limit, 3%.

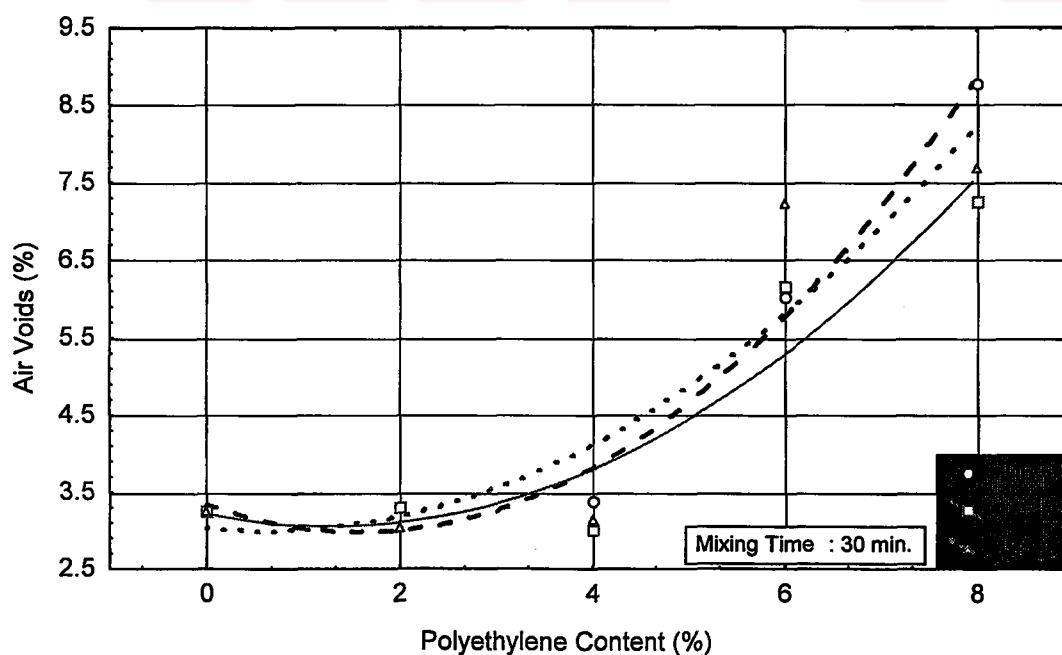


Figure 5.47 Air Voids vs polyethylene content for 30 min. mixing time

For 30 min. mixing the 145°C and 155°C curves display a similar trend between 0-4% HDP. They have a common minimum at of 2% HDP, the percentage of air voids being at the lower of acceptable limits. The 165°C mixing appear to be insensitive to mixing period.

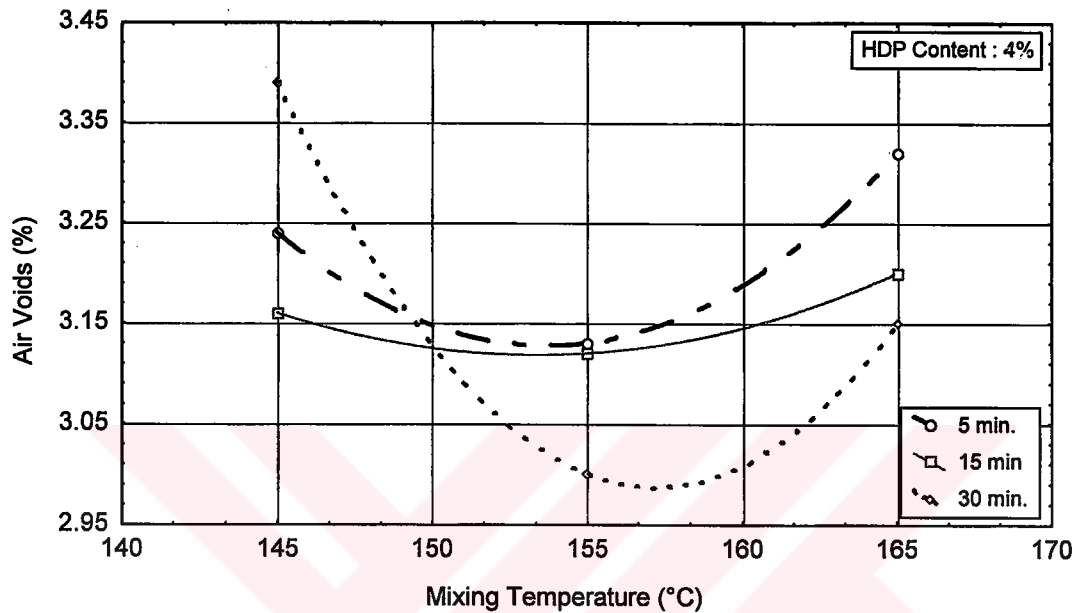


Figure 5.48 Air voids vs mixing temperature for 4% HDP content

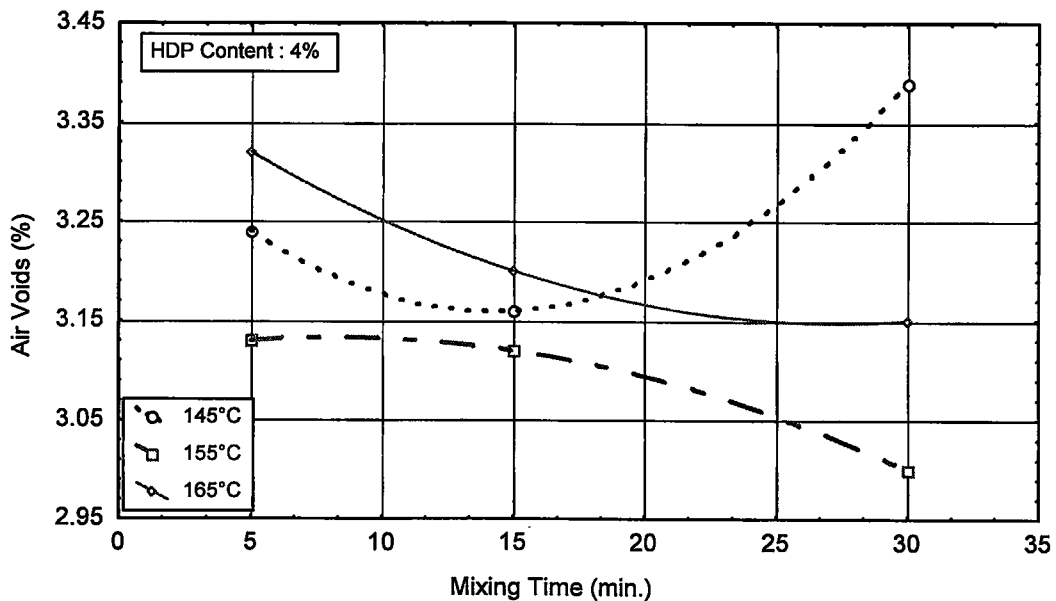


Figure 5.49 Air voids vs mixing time for 4% HDP content

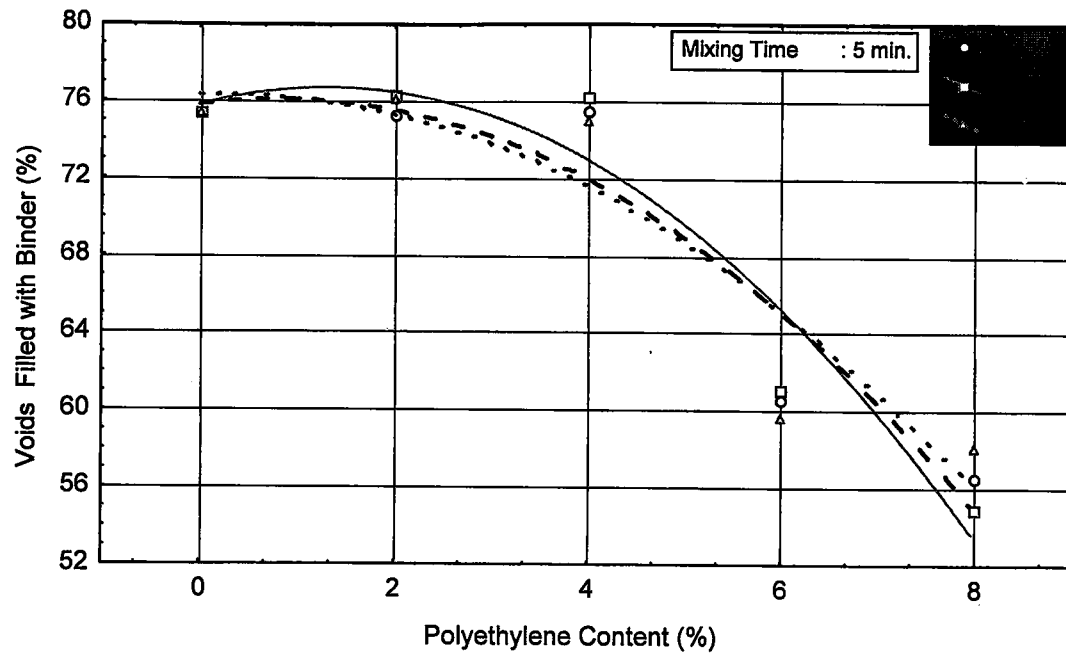


Figure 5.50 Voids filled with binder vs polyethylene content for 5 min. mixing time

In the Figure 5.50, the variation of percent voids filled with binder is displayed against polyethylene content for 5 min. mixing. The plots corresponding to 145° C and 165° C temperatures show a steady and parabolic decrease in voids filled with increasing polyethylene content. For 155° C mixing temperature, however, the percent of voids filled slightly increases up to 1.8% polyethylene making a maximum and decreases there after.

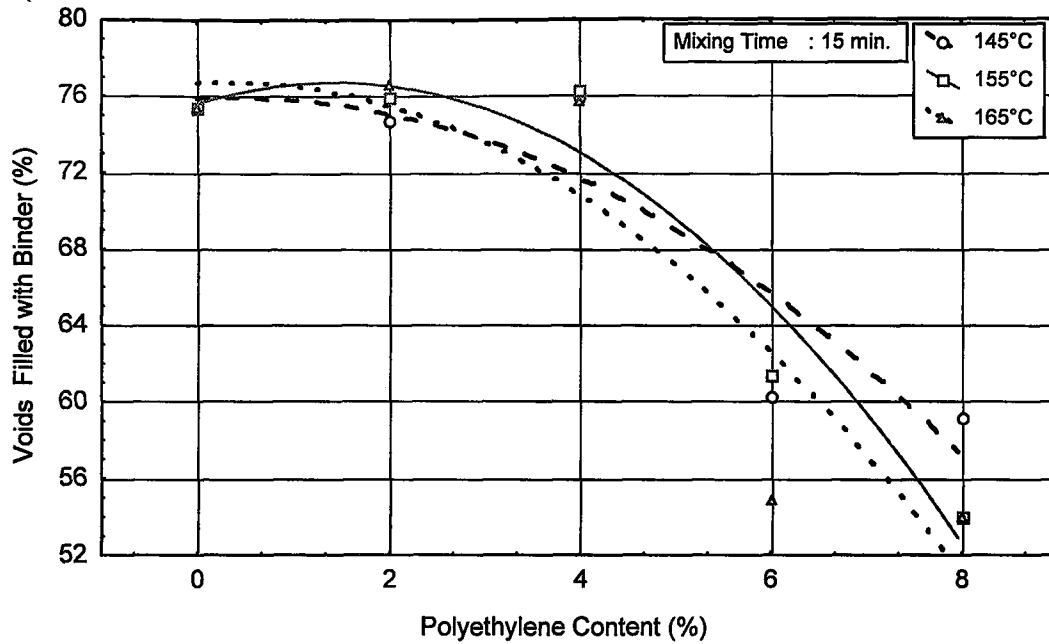


Figure 5.51 Voids filled with binder vs polyethylene content for 15 min. mixing time

This graph depicts the change in percentage of voids filled with binder with varying polyethylene contents for 15 min. mixing. The superiority of mixing at 155°C is more pronounced for this mixing time. The performances of mixing at 145°C and 165°C come out to be poorer for this mixing time as compared to 5 min. mixing.

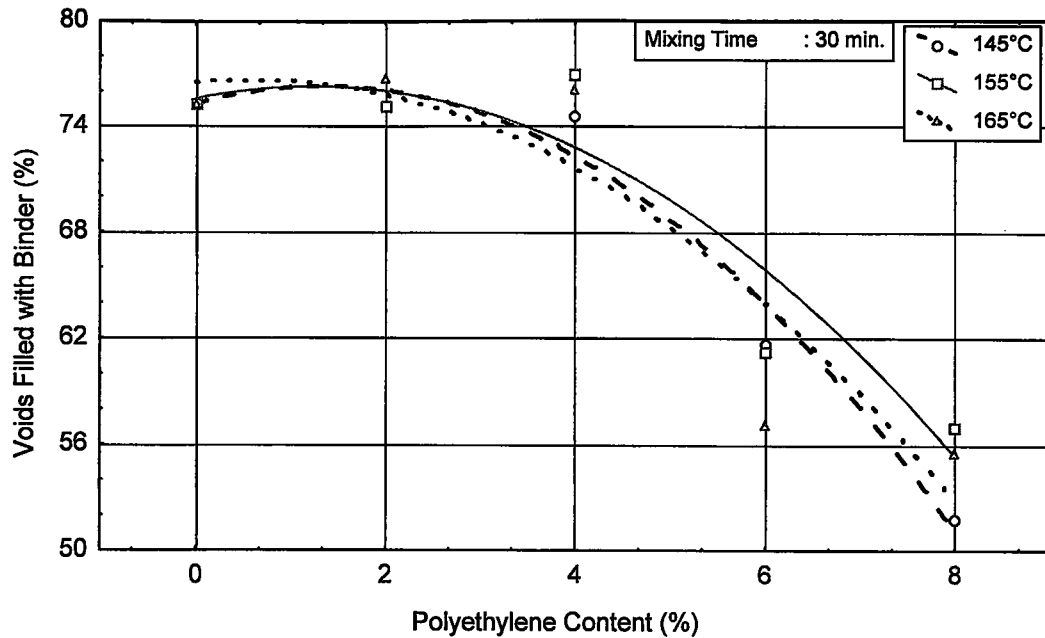


Figure 5.52 Voids filled with binder vs polyethylene content for 30 min. mixing time

From this graph, it is clear that prolonging the mixing time contributes to the mixing at 145°C, yet almost no improvement can be mentioned for mixing at 155°C. Hence, it can be concluded that mixing at 145°C for 30 min. and mixing at 155°C for 15 min. gives almost the same results.

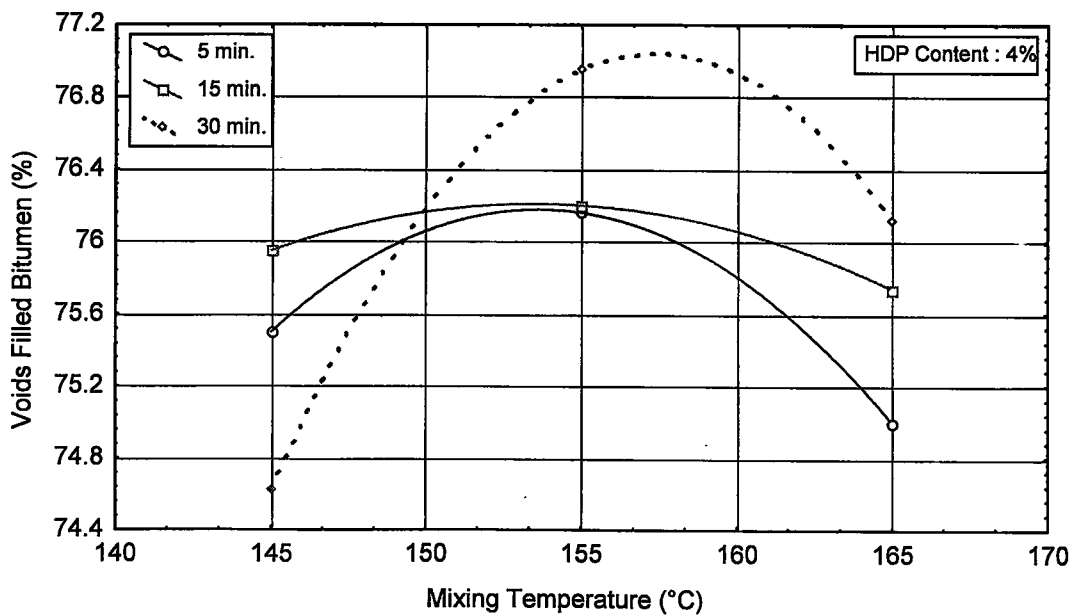


Figure 5.53 Voids filled with bitumen vs mixing temperature for 4% HDP content

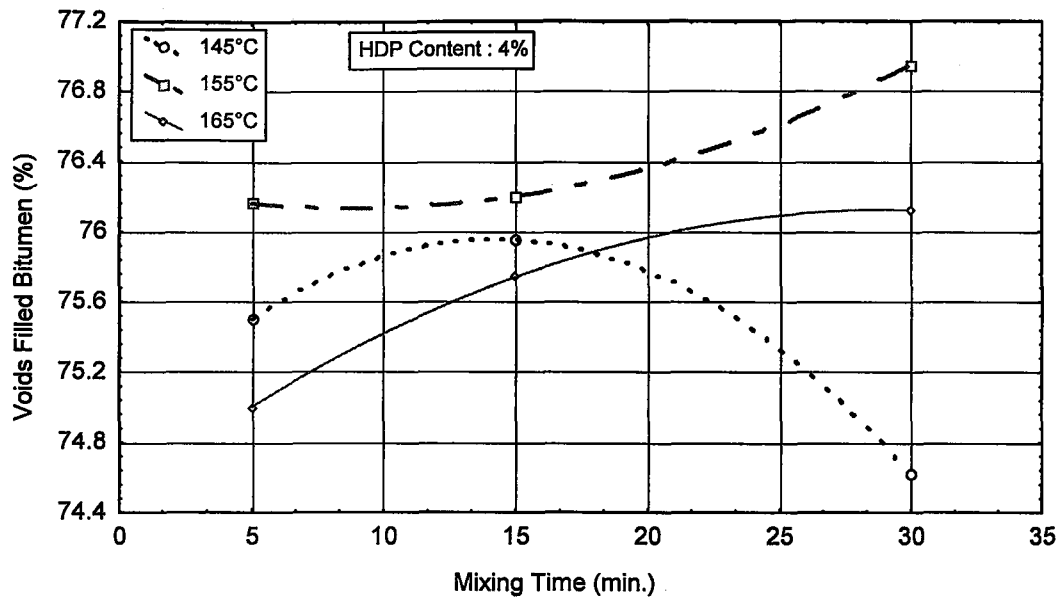


Figure 5.54 Voids filled with bitumen vs mixing time for 4% HDP content

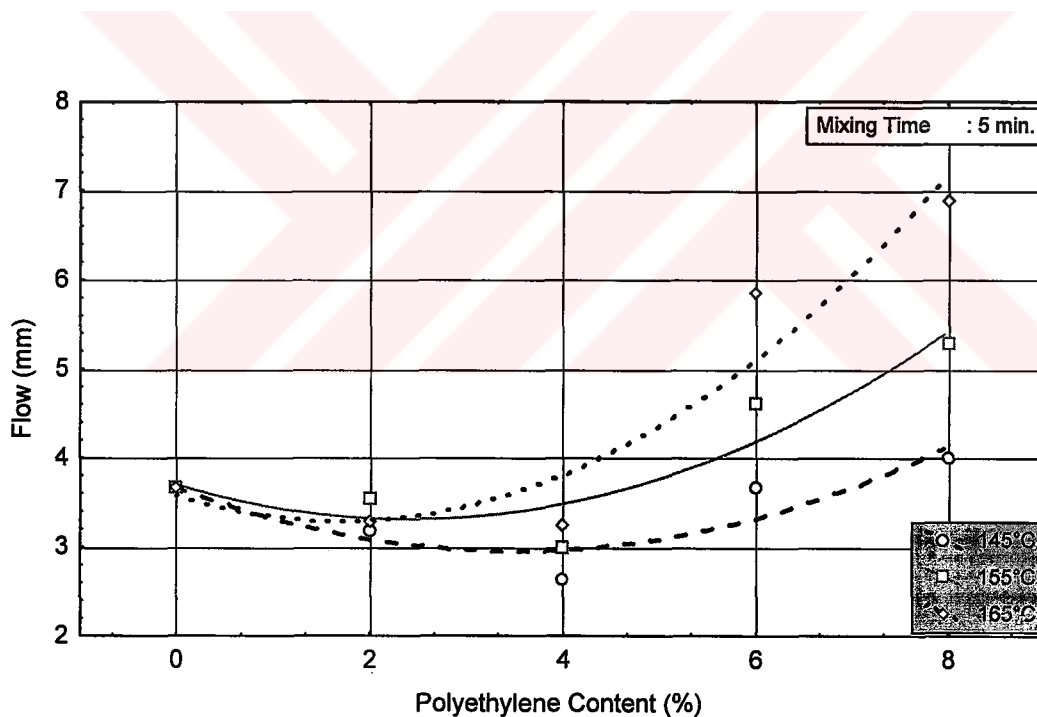


Figure 5.55 Flow vs polyethylene content for 5 min. mixing time

Flow is an indication of rutting in asphalt concrete. This graph displays the flow against polyethylene content. The graph demonstrates the positive effect of polyethylene in reducing flow. However, at 145°C mixing this effect is more pronounced. And it is seen that the minimum flow is observed with 4% polyethylene at 145°C mixing temperature.

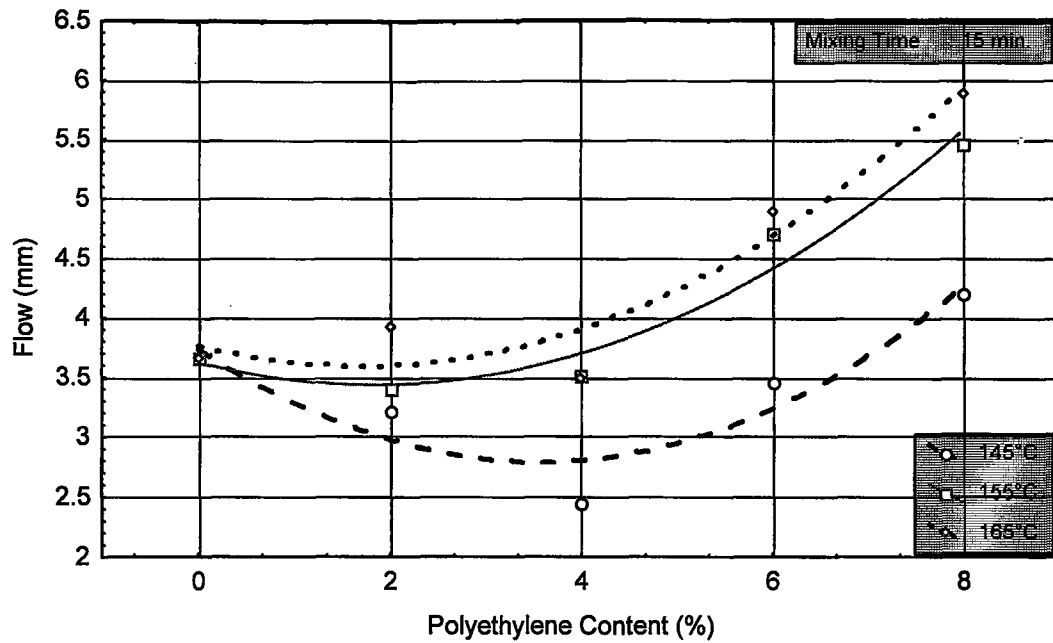


Figure 5.56 Flow vs polyethylene content for 15 min. mixing time

Figure 5.56 shows the effect of polyethylene content on flow for 155 and 165°C mixing temperatures. The prolonged mixing time has even more improved the flow values for 145°C mixing

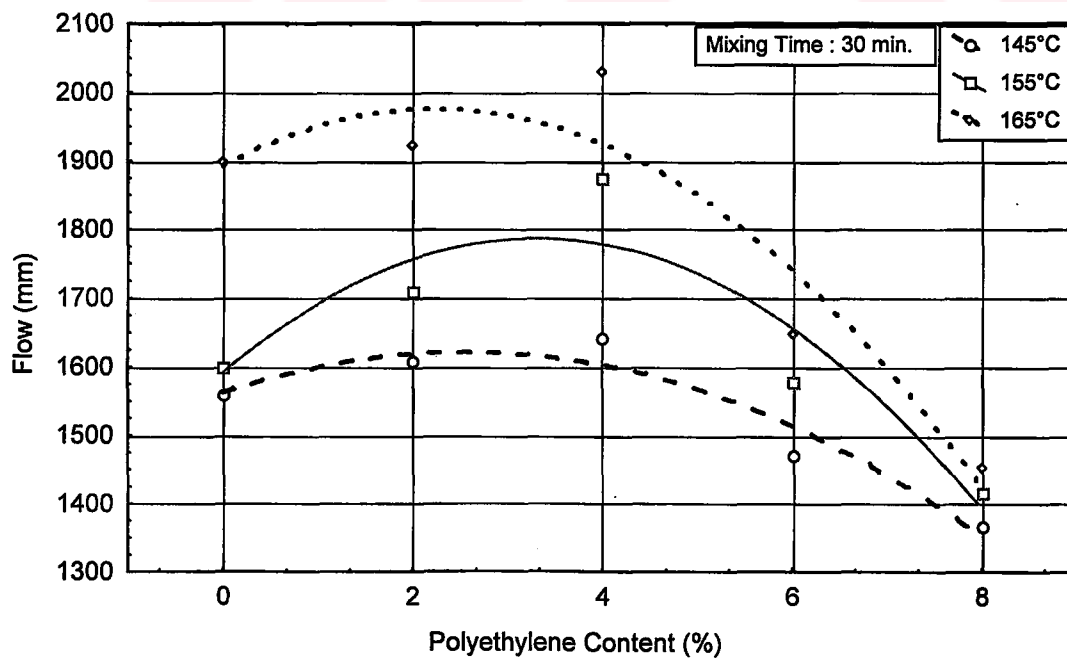


Figure 5.57 Flow vs polyethylene content for 30 min. mixing time

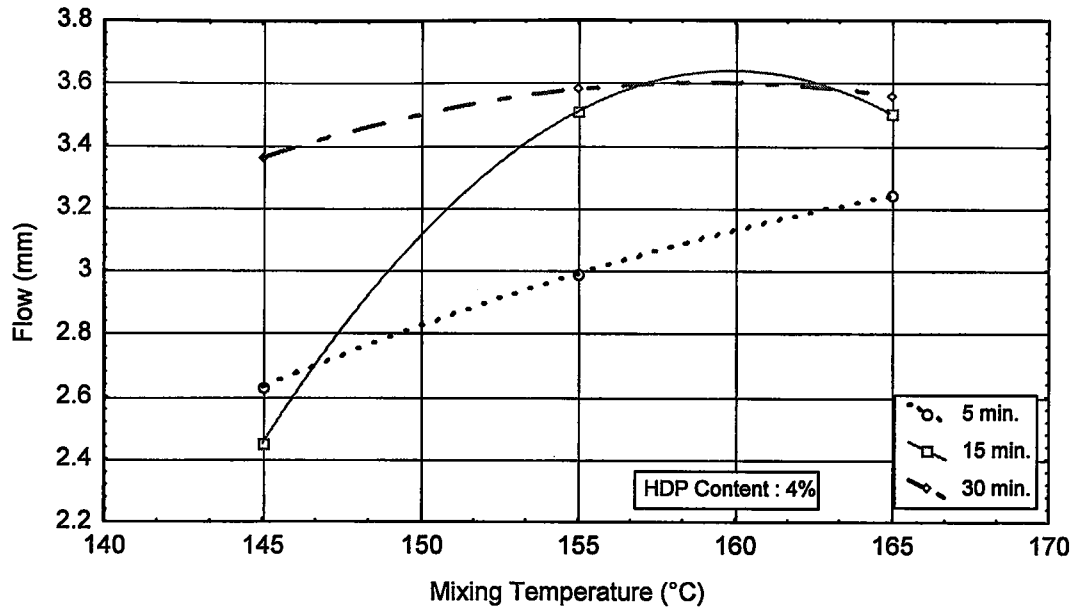


Figure 5.58 Flow vs mixing temperature for 4% HDP content

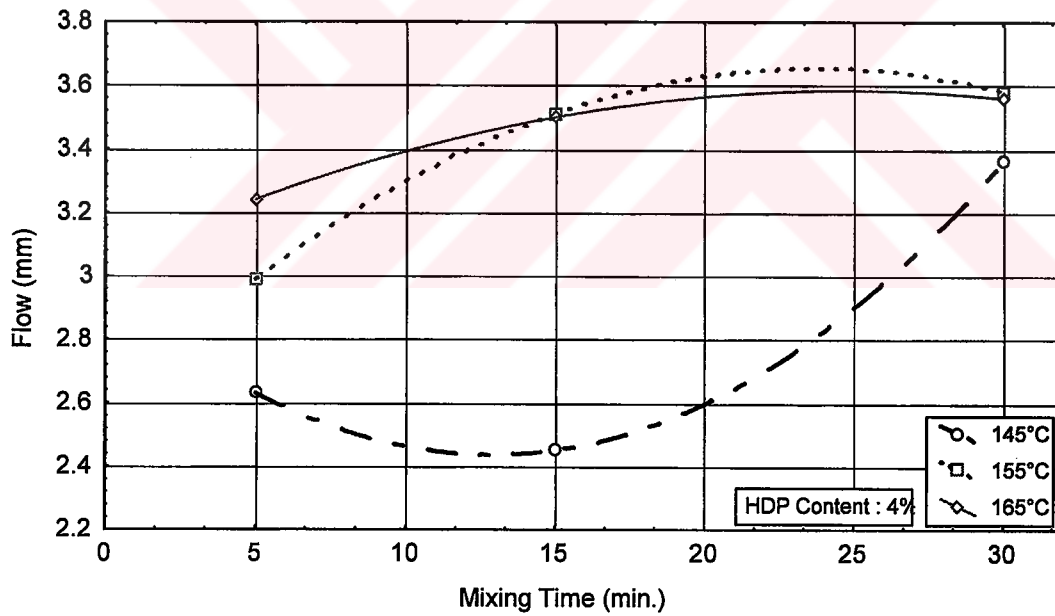


Figure 5.59 Flow vs mixing time for 4% HDP content

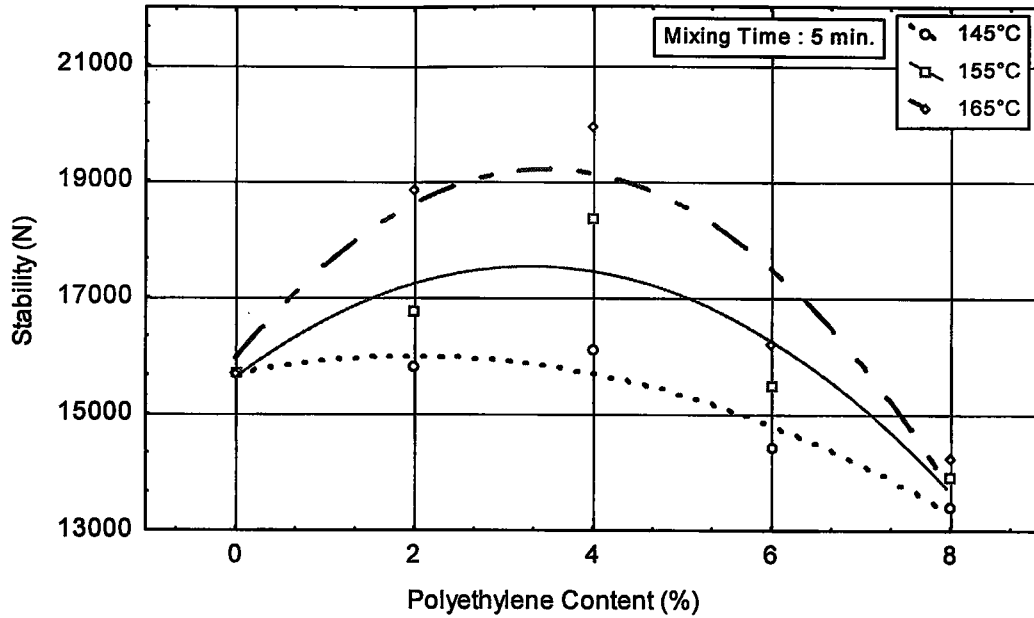


Figure 5.60 Stability vs polyethylene content for 5 min. mixing time

The stability of specimen versus polyethylene content for 5 min. mixing time is depicted on the graph above. The stability of specimens mixed at 165°C are significantly higher than those prepared at 145°C. Polyethylene content around 4% gives the best stability.

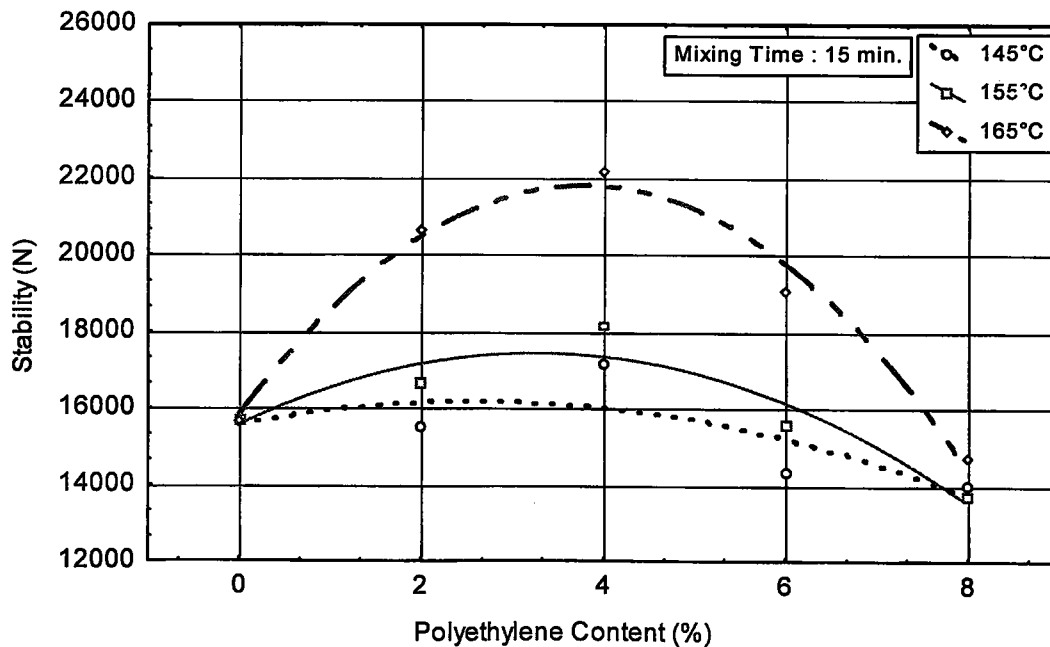


Figure 5.61 Stability vs polyethylene content for 15 min. mixing time

In this graph, the superiority of 165°C mixing temperature with regard to stability is highly pronounced. While the stability levels of 145°C and 155°C do not change much from that of 5 min. mixing, the maximum stability obtained for 165°C mixing has significantly improved, the maximum value being at 4% polyethylene content.

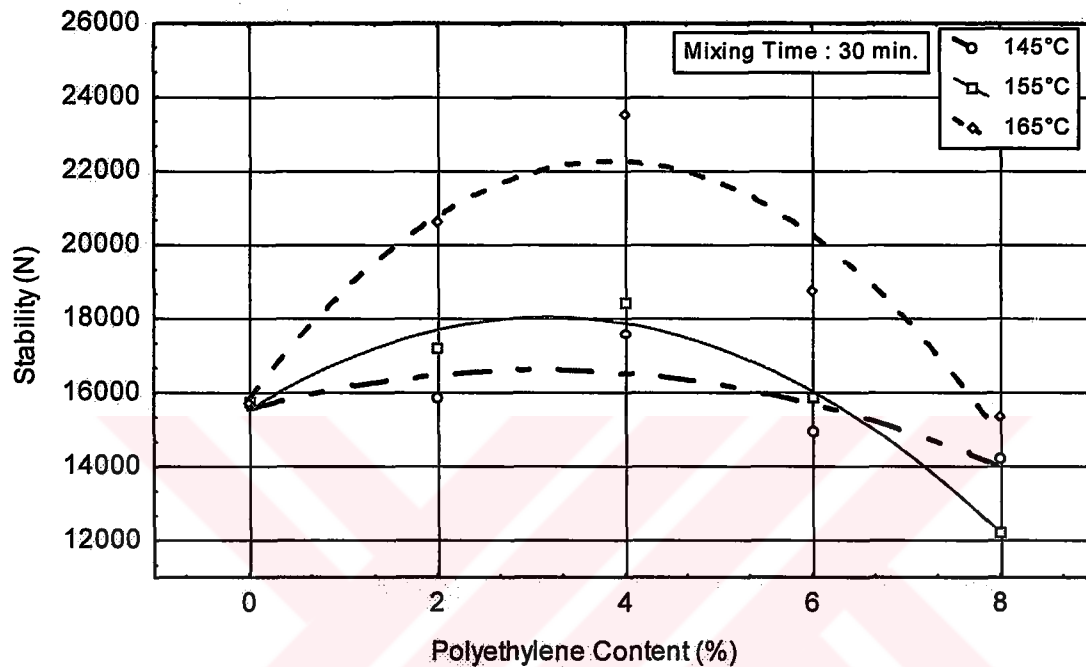


Figure 5.62 Stability vs polyethylene content for 30 min. mixing time

In this graph, the stability of the asphalt specimens for 30 min. mixing are plotted against polyethylene content. The best stability is obtained at 165°C mixing temperature comparison of this graph and those for 5 min. and 15 min. mixing times indicates that stability is proportional both to mixing temperature, and mixing time.

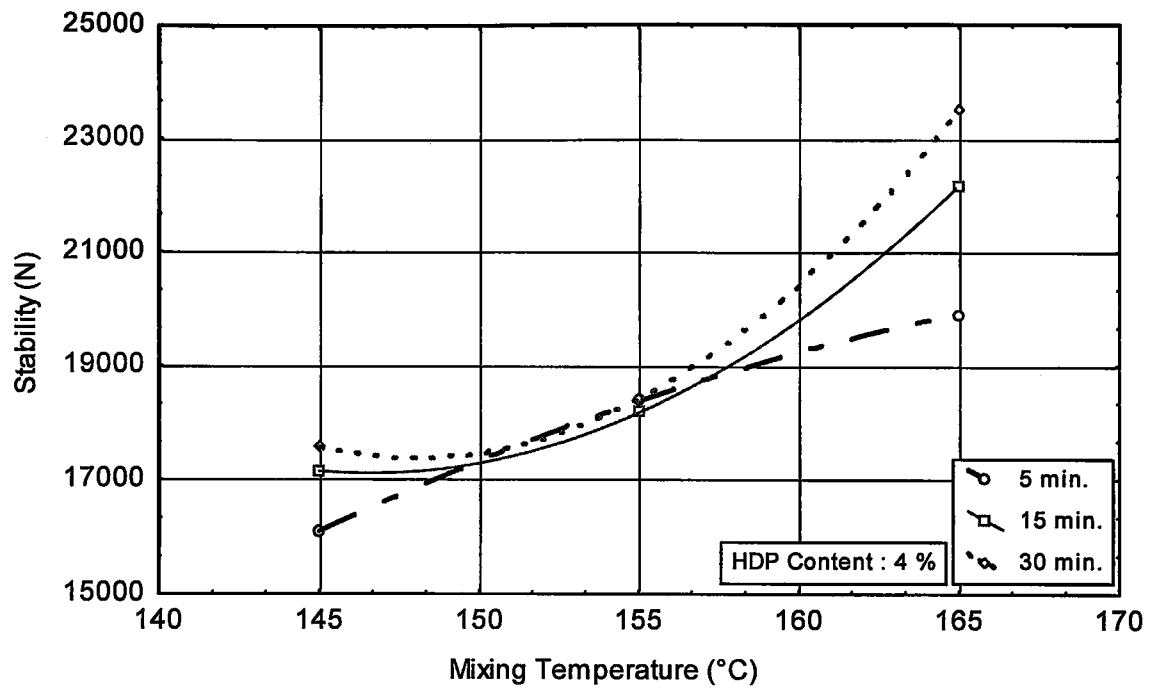


Figure 5.63 Stability vs mixing temperature for 4% HDP content

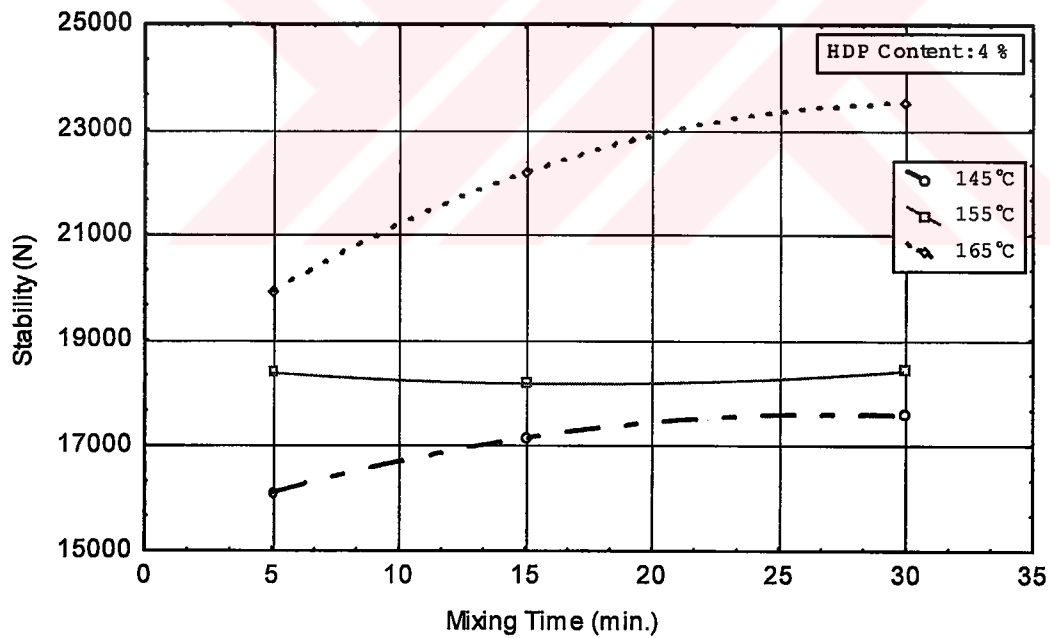


Figure 5.64 Stability vs mixing time for 4% HDP content

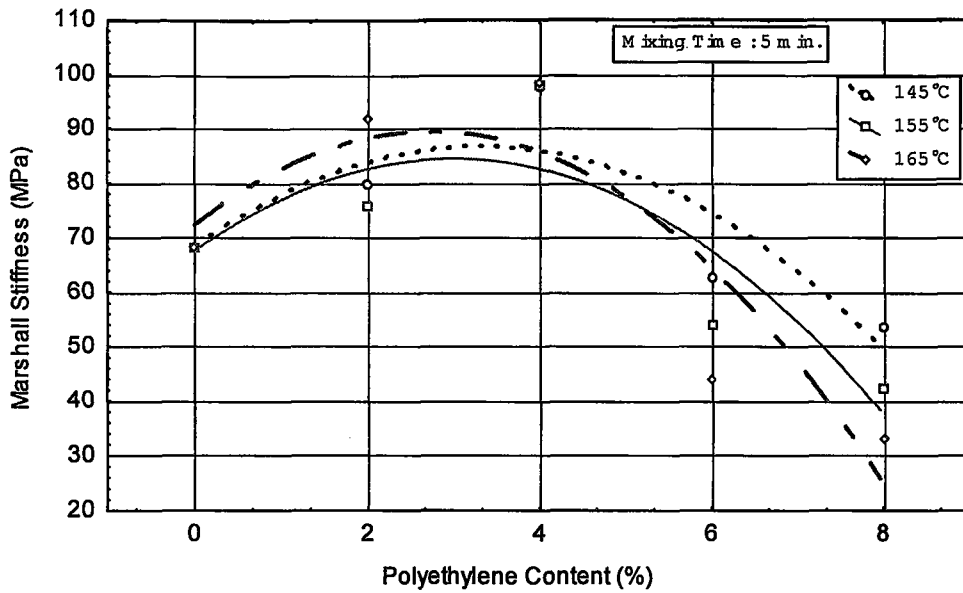


Figure 5.65 Marshall stiffness vs polyethylene content for 5 min. mixing time

This graph shows the change in Marshall Stiffness with polyethylene content. For 5 min. mixing time the optimum polyethylene content for the three mix times is around 3.0%. It is seen from the graph that higher mixing temperatures give higher Marshall Stiffnesses.

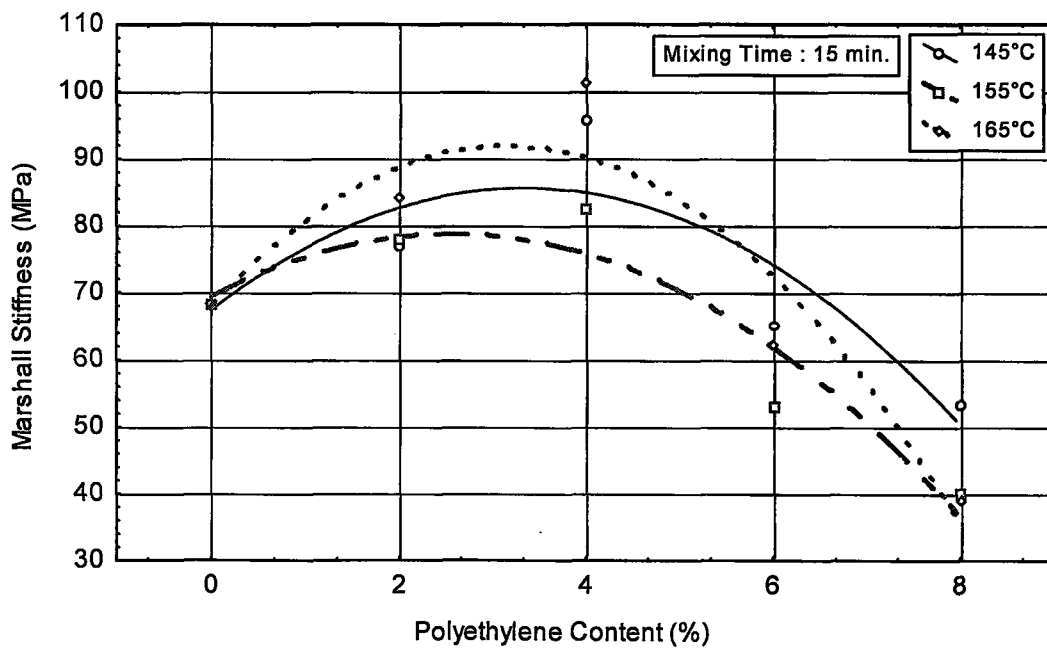


Figure 5.66 Marshall stiffness vs polyethylene content for 15 min. mixing time

This graph plots Marshall Stiffnesses obtained for 15 min. mixing time. The 165 and 155°C curves seems unaffected from increasing mixing time from 5 min. to 15 min., yet the stiffness values for 145°C mixing has decreased somewhat. Again the optimum polyethylene content can be inferred to be around 3%.

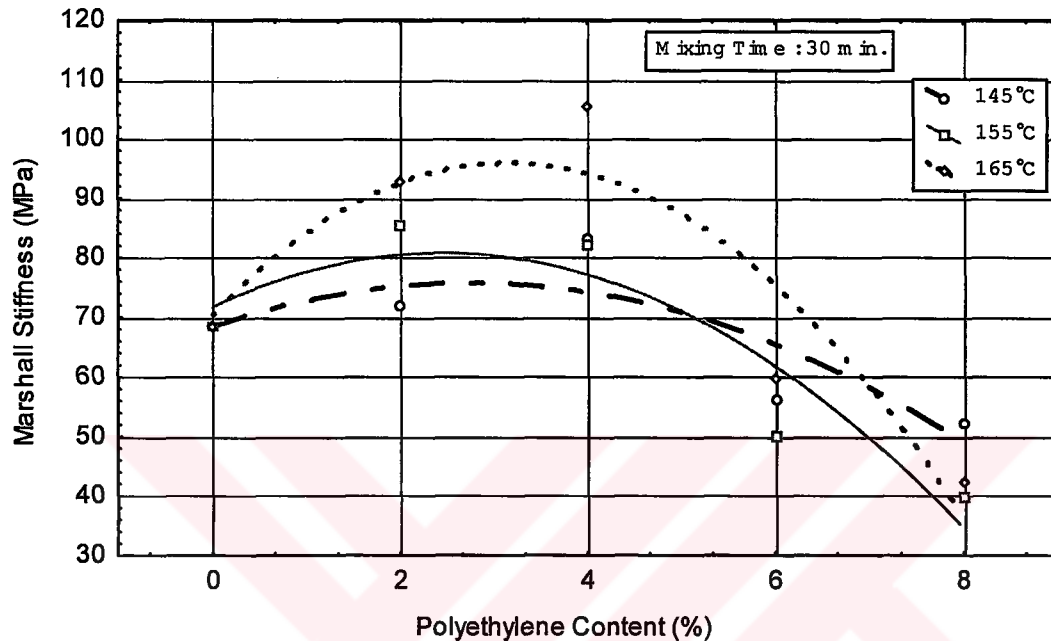


Figure 5.67 Marshall stiffness vs polyethylene content for 30 min. mixing time

The 30 min. mixing time pronounces the differences between mixing temperatures. Marshall Stiffness values for 165°C mixing temperatures are even higher, whereas those corresponding to 155 and 145°C mixing has dropped significantly. As a result, prolonged mixing times and higher mixing temperatures give rise to higher Marshall Stiffness. The higher the mixing temperature and the longer the mixing time, the higher will be the Marshall Stiffness. The graphs indicate that 4% polyethylene content gives the highest Marshall Stiffness.

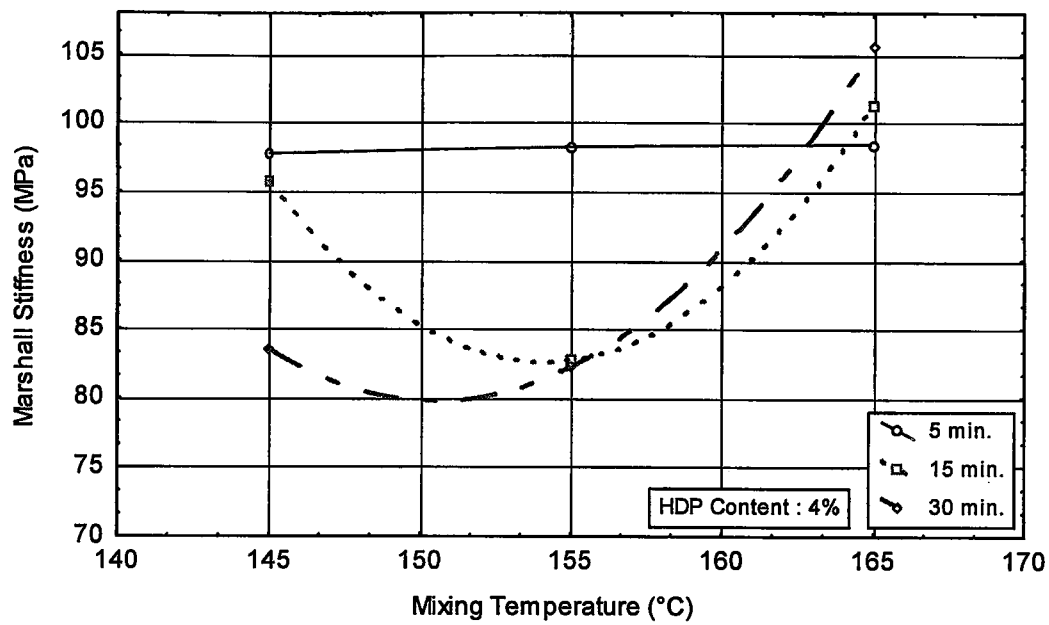


Figure 5.68 Marshall stiffness vs mixing temperature for 4% HDP content

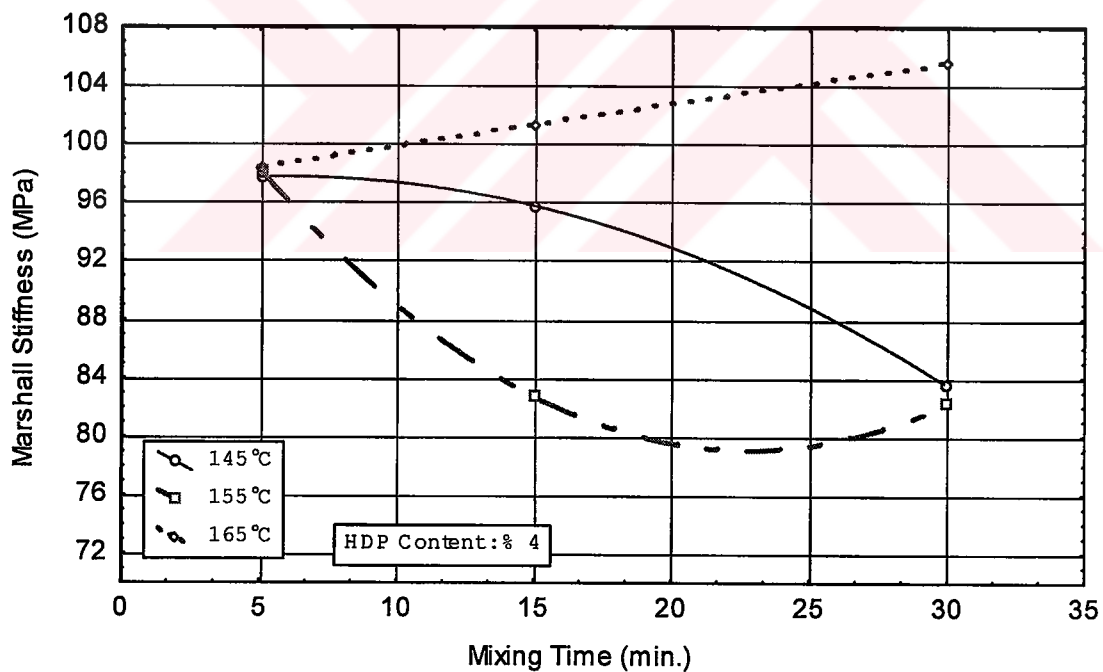


Figure 5.69 Marshall stiffness vs mixing time for 4% HDP content

Marshall stability is an indicator of rutting resistance [6]. Asphalt concrete specimens were compacted at the plant site in accordance with the requirements of

the Standard Test Method for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus (ASTM D 1559-89).

Result presented in Figure 5.60 to 5.64 indicated that the polymerized asphalt mix had a higher Marshall stability than other unmodified mixes. **It may be concluded that the polymerized asphalt mix is less susceptible to plastic deformation as characterized by Marshall stability.**

These findings were later verified by resilient modulus tests; that is, a relatively close correlation between the two results was observed.

The graphics have also been plotted to see the effect of the mixing time on the Marshall properties. These graphics are as follows.

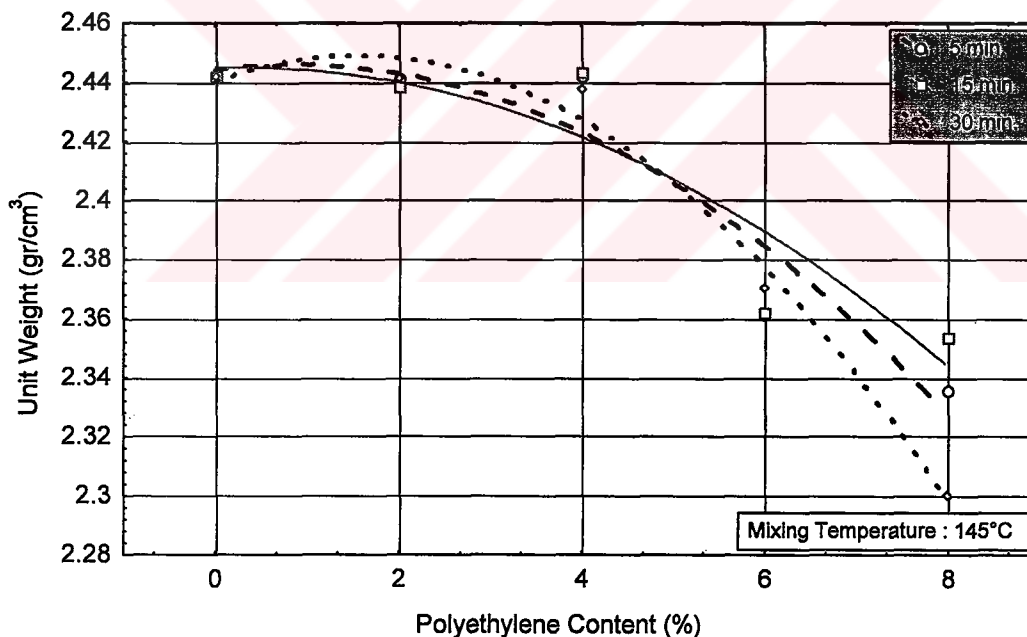


Figure 5.70 Unit weight vs Polyethylene content for 145°C mixing temperature

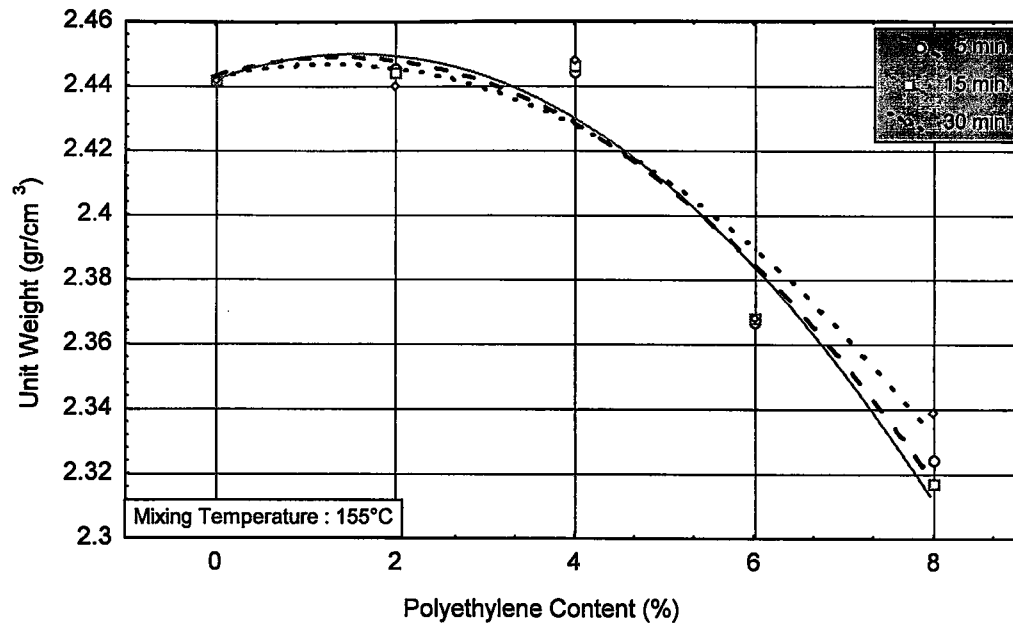


Figure 5.71 Unit weight vs Polyethylene content for 155°C mixing temperature

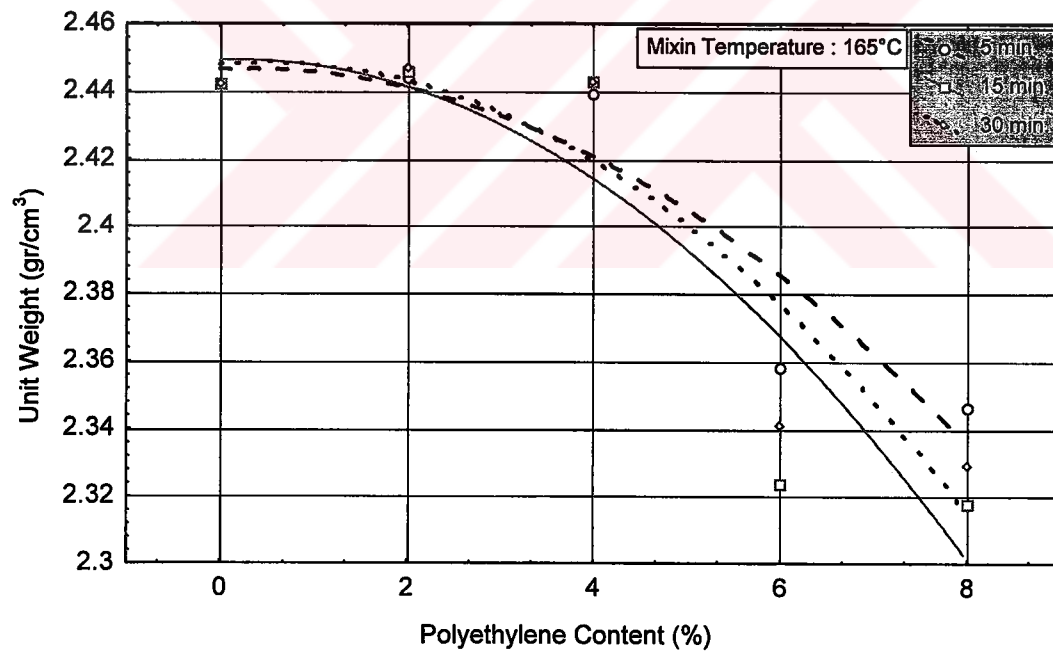


Figure 5.72 Unit weight vs Polyethylene content for 165°C mixing temperature

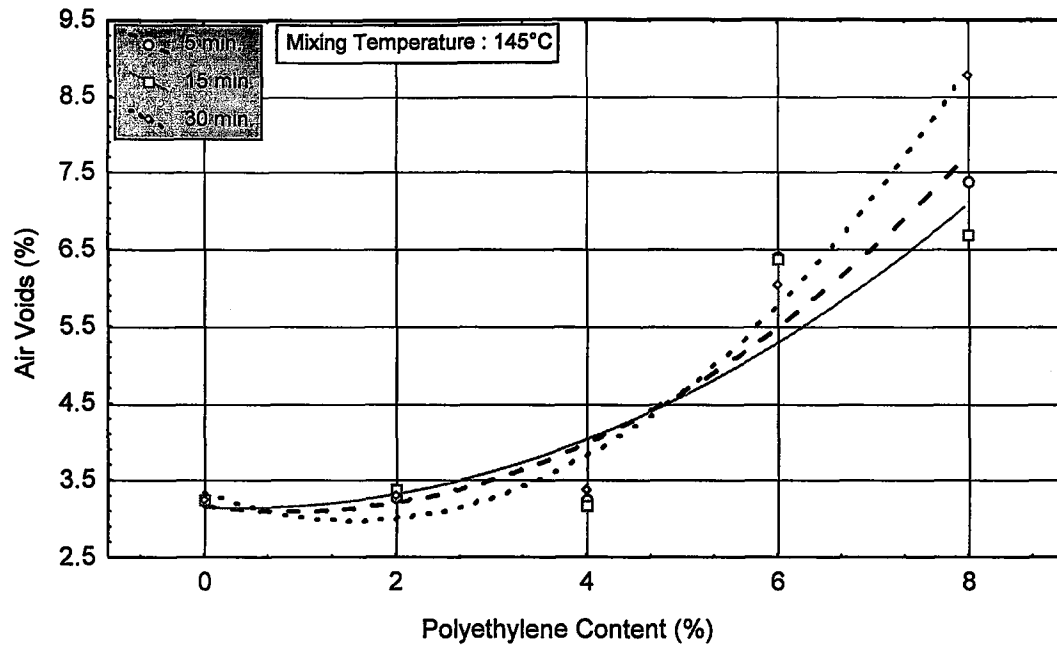


Figure 5.73 Air voids vs Polyethylene content for 145°C mixing temperature

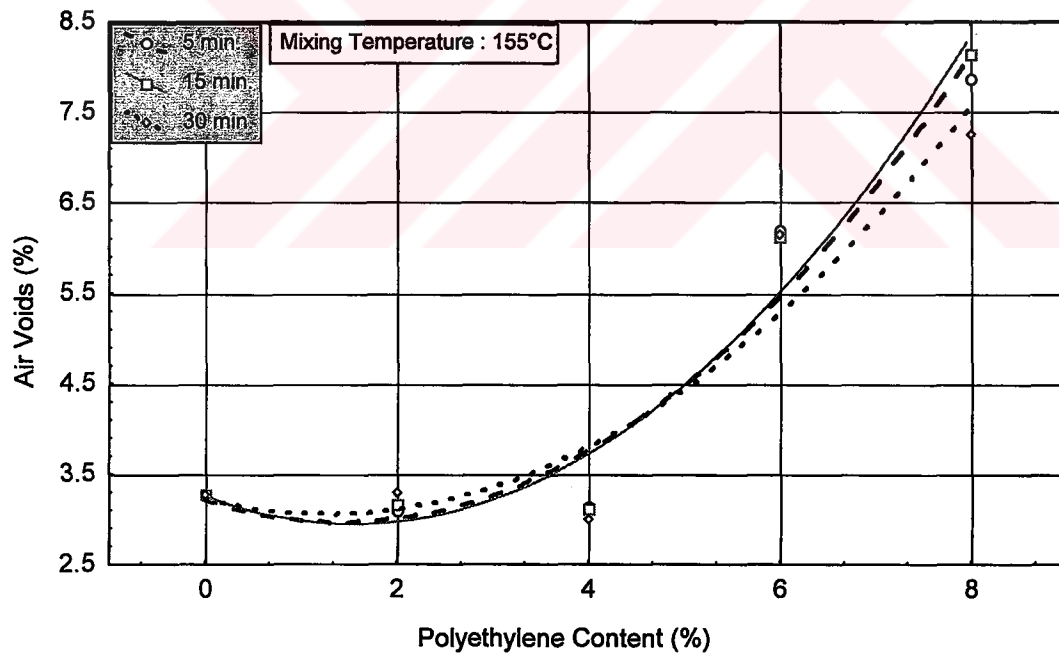


Figure 5.74 Air voids vs Polyethylene content for 155°C mixing temperature

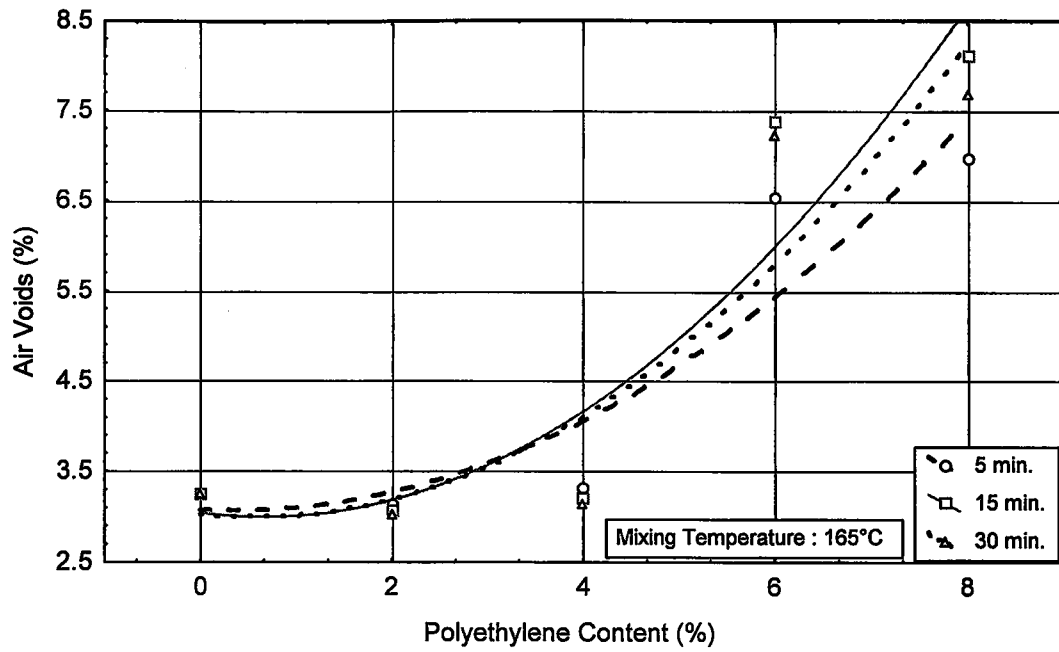


Figure 5.75 Air voids vs polyethylene content for 165°C mixing temperature

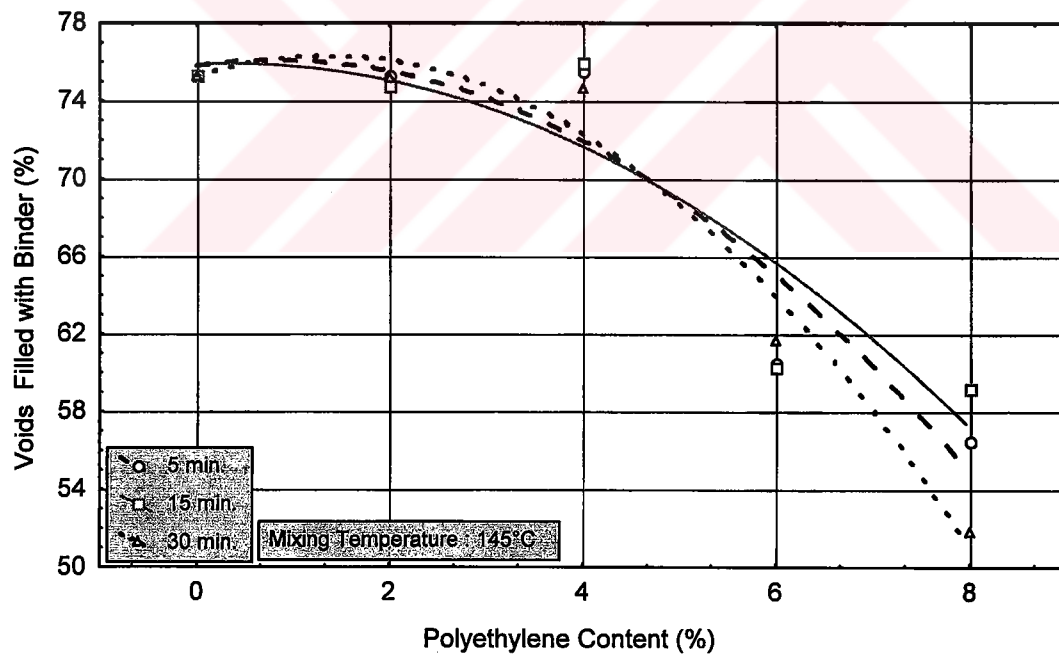


Figure 5.76 Voids filled with binder vs polyethylene content for 145°C mixing temperature

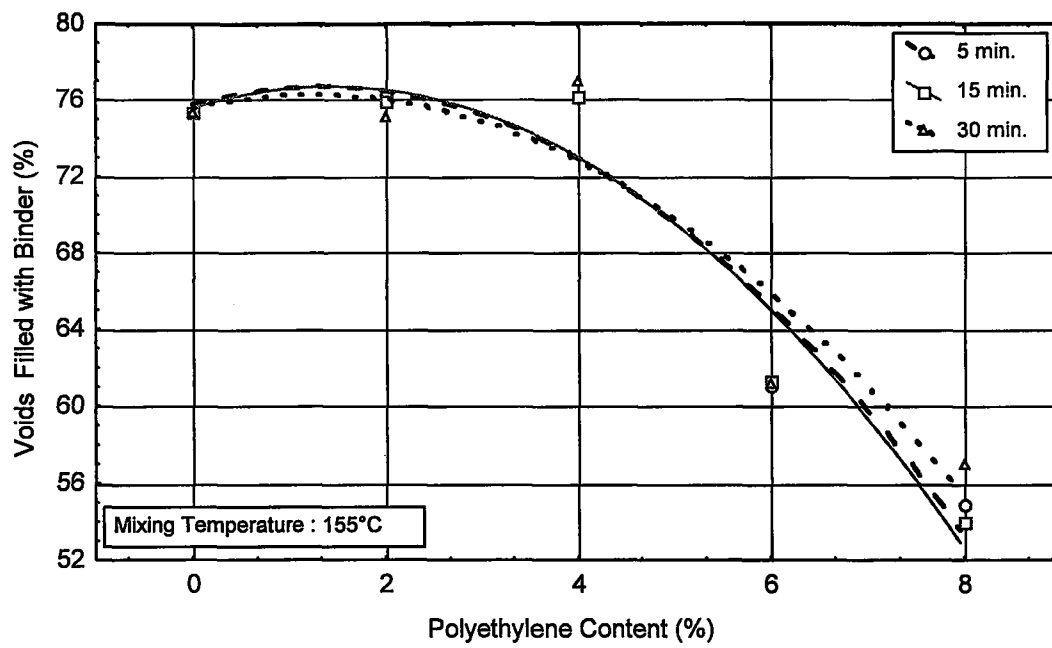


Figure 5.77 Voids filled with binder vs polyethylene content for 155°C mixing temperature

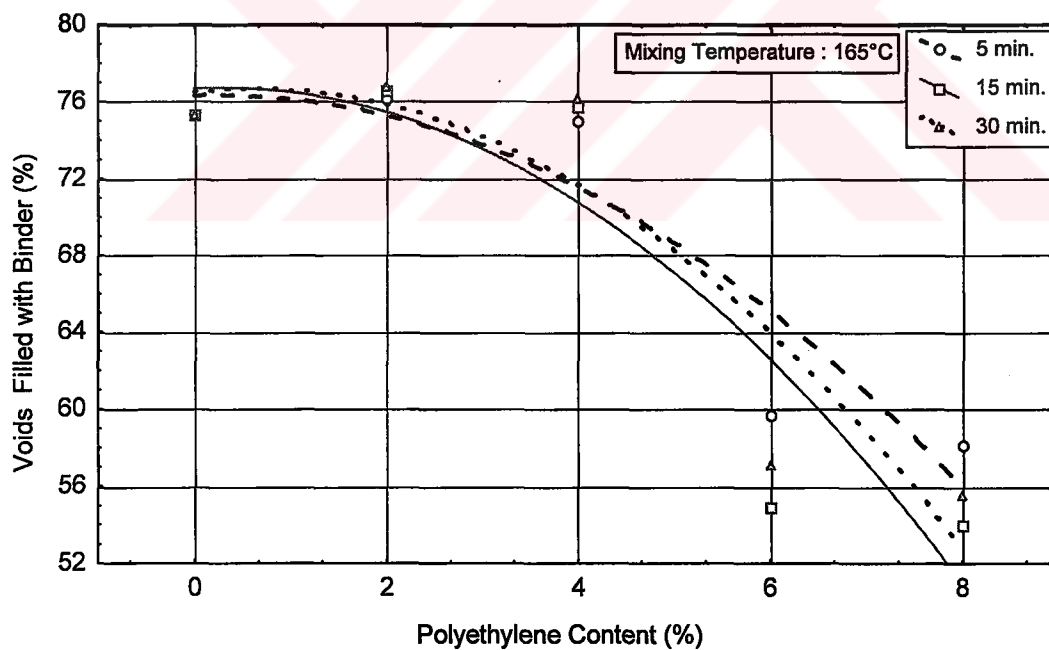


Figure 5.78 Voids filled with binder vs polyethylene content for 165°C mixing temperature

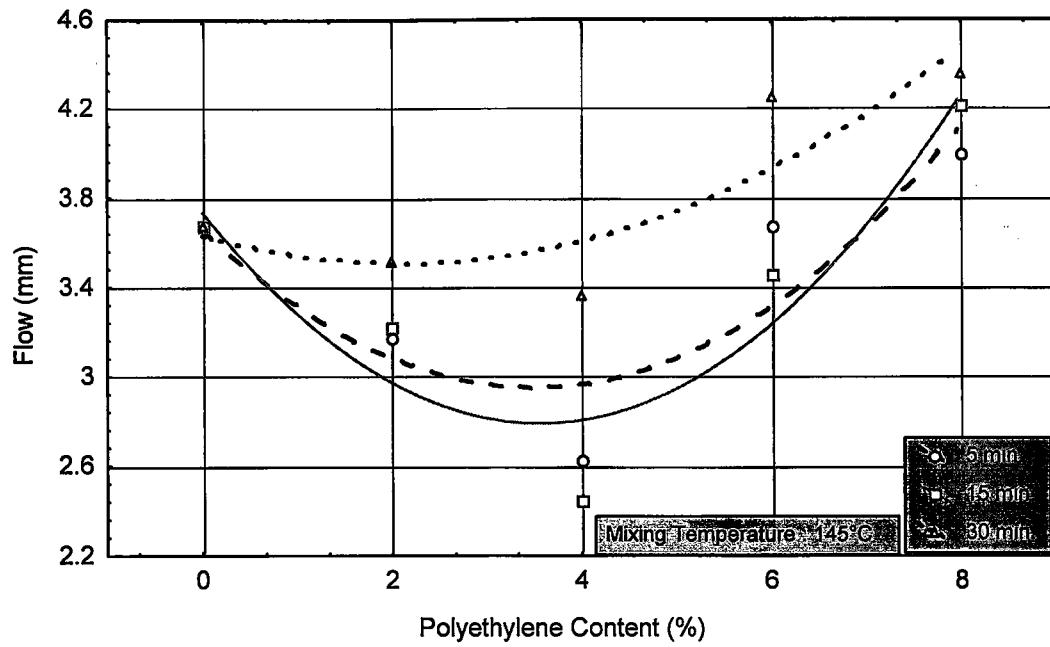


Figure 5.79 Flow vs polyethylene content for 145°C mixing temperature

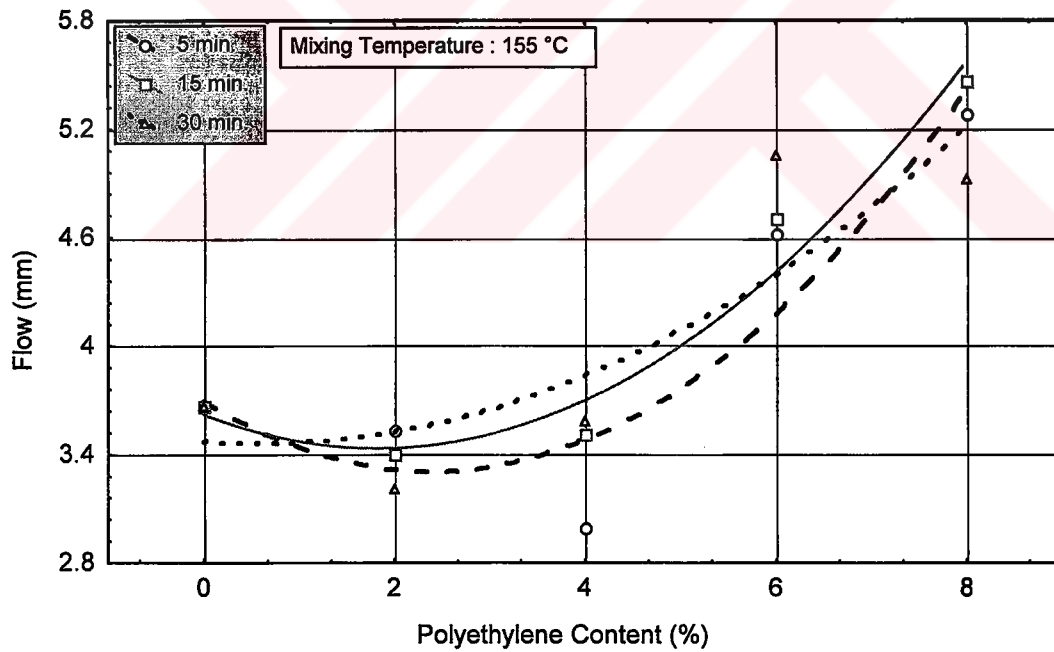


Figure 5.80 Flow vs polyethylene content for 155°C mixing temperature

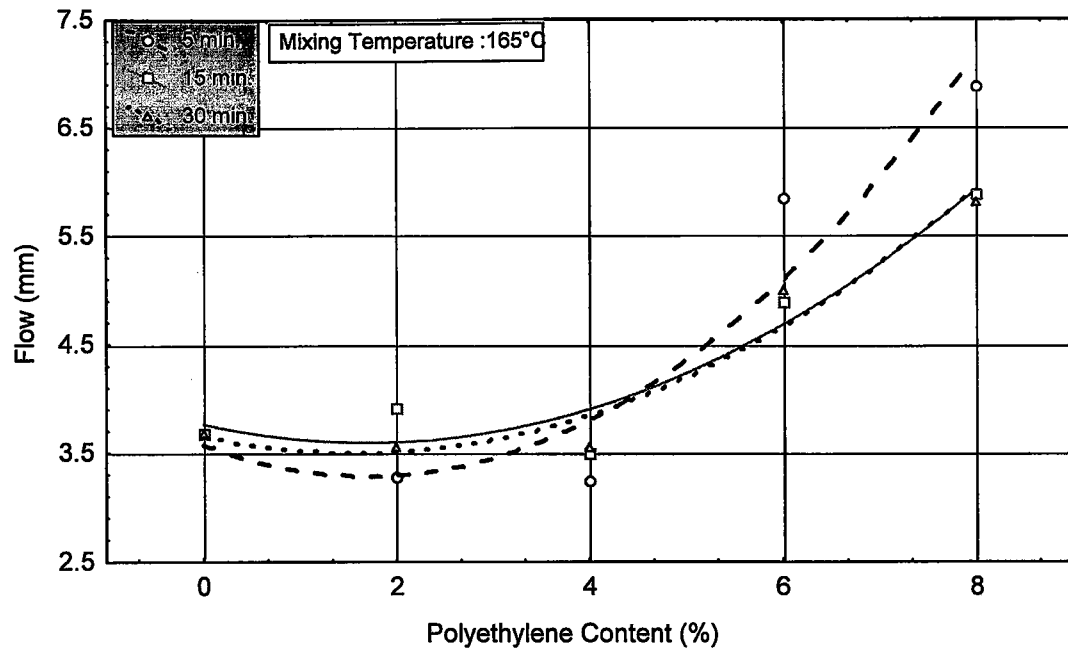


Figure 5.81 Flow vs polyethylene content for 165°C mixing temperature

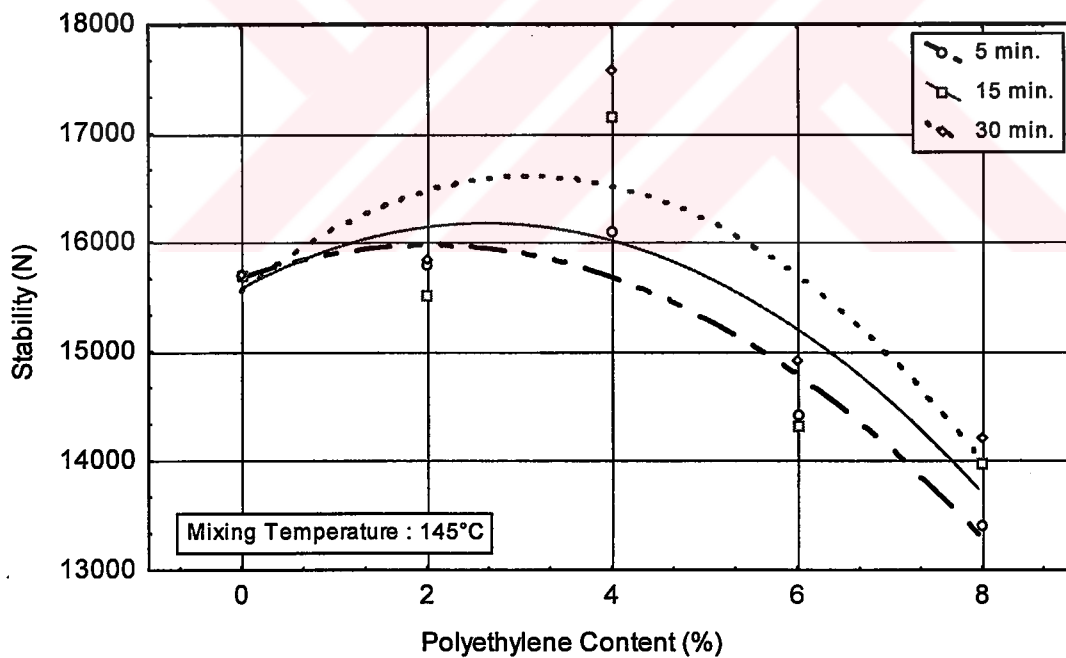


Figure 5.82 Stability vs polyethylene content for 145°C mixing temperature

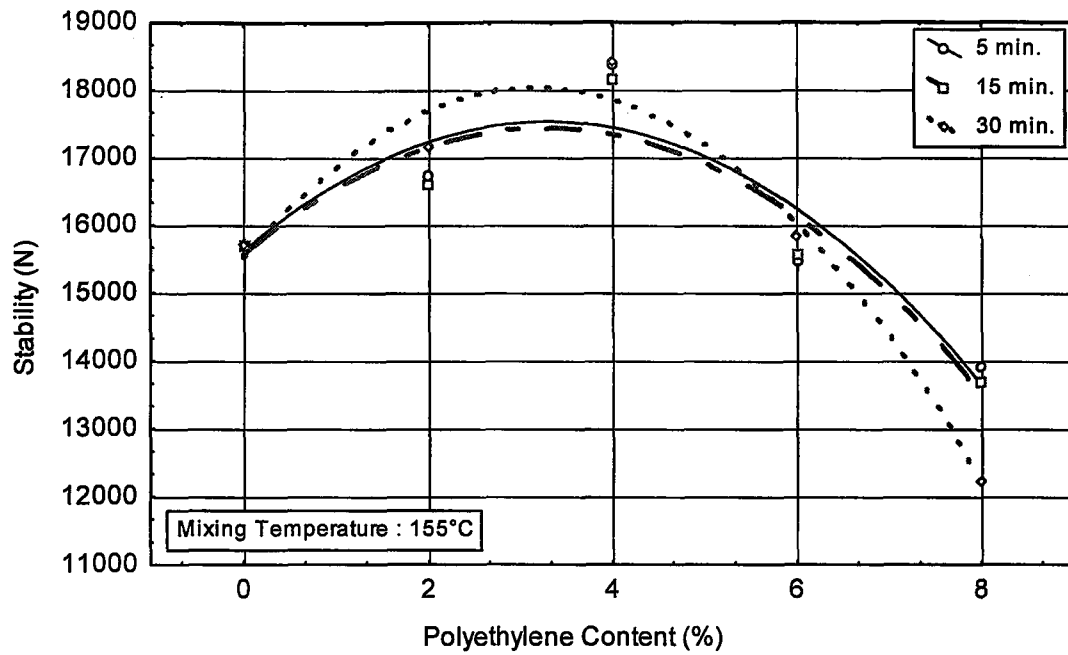


Figure 5.83 Stability vs polyethylene content for 155°C mixing temperature

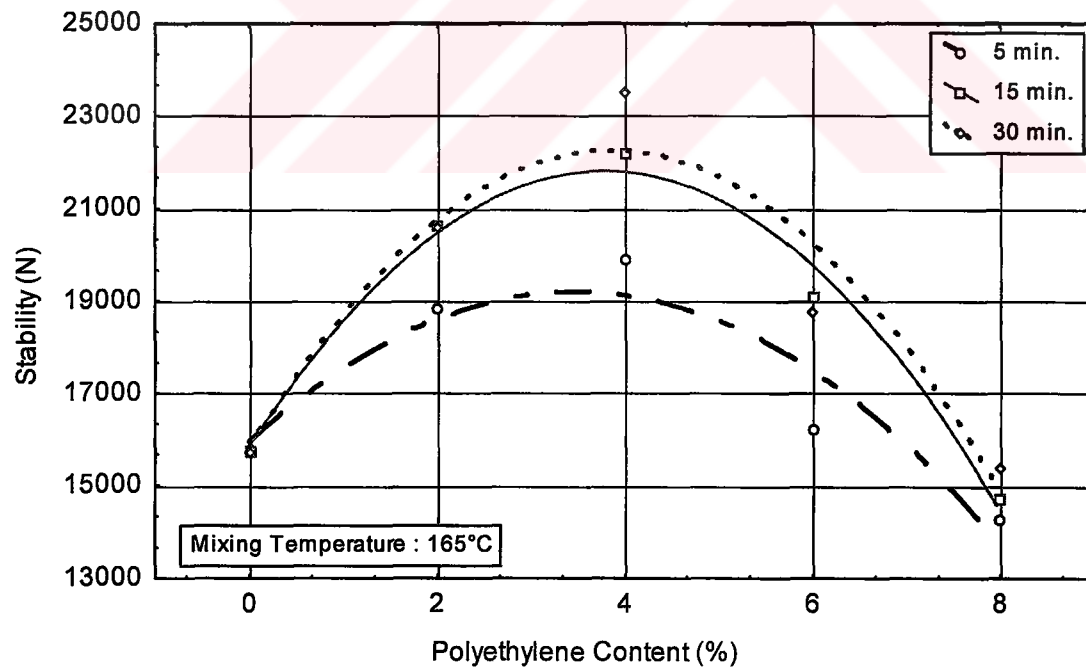


Figure 5.84 Stability vs polyethylene content for 165°C mixing temperature

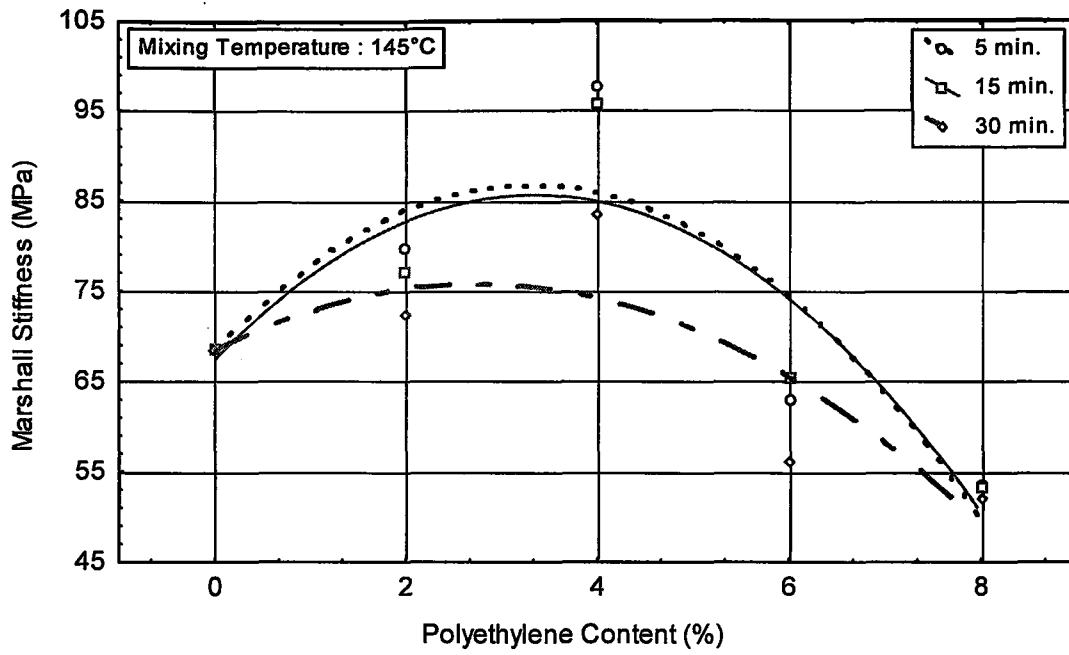


Figure 5.85 Marshall stiffness vs polyethylene content for 145°C mixing temperature

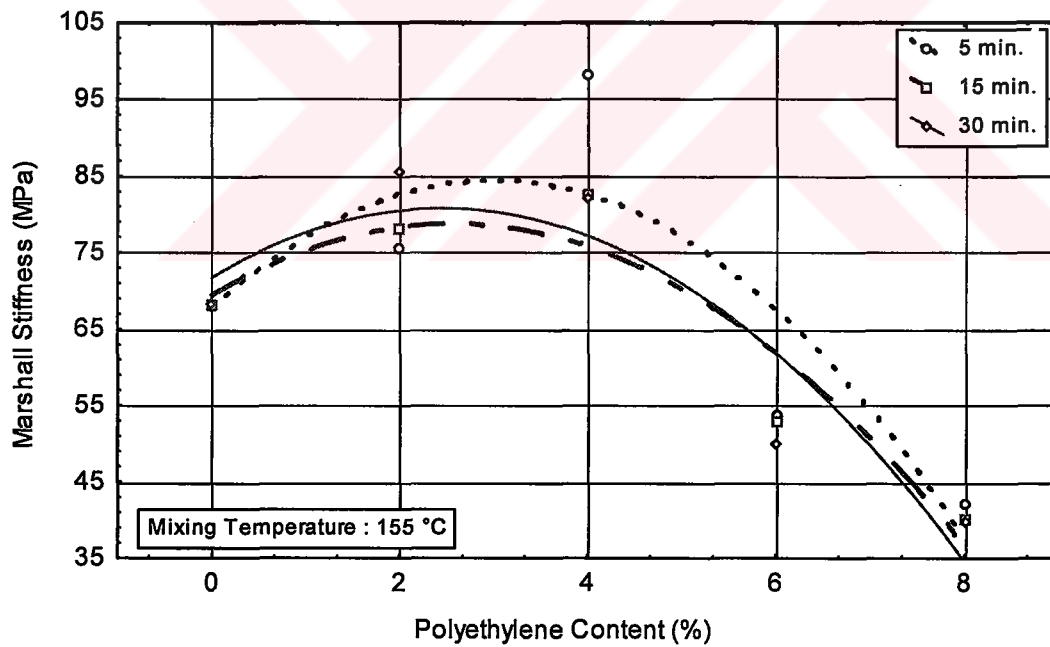


Figure 5.86 Marshall stiffness vs polyethylene content for 155°C mixing temperature

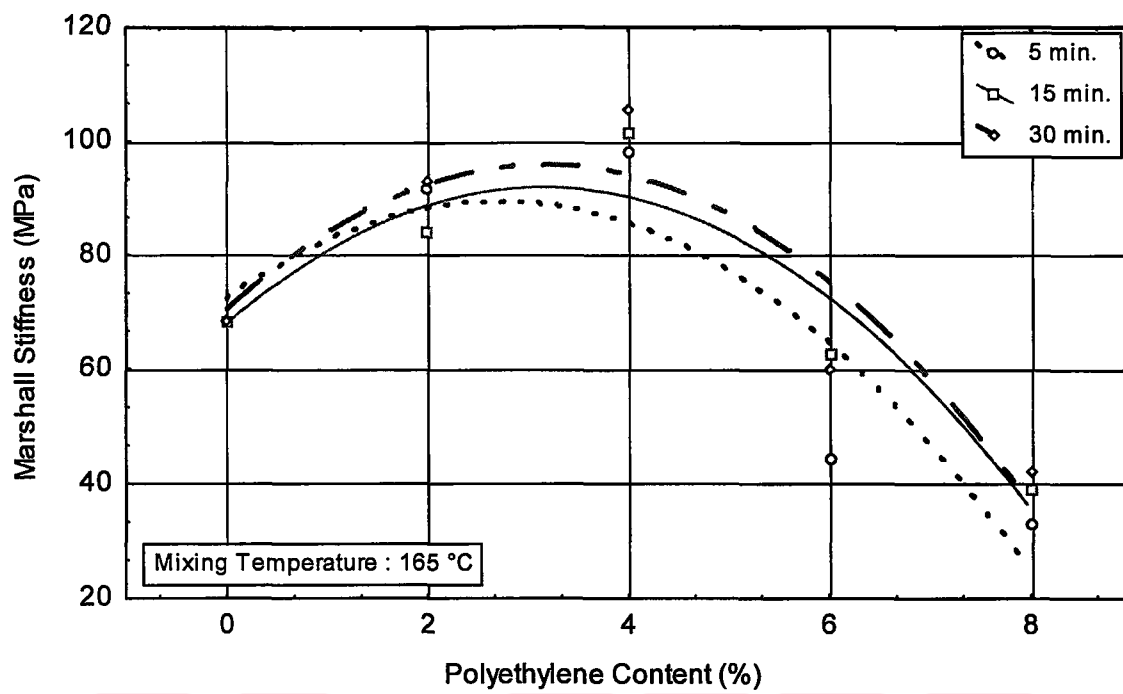


Figure 5.87 Marshall stiffness vs polyethylene content for 165°C mixing temperature

5.8 RESILIENT MODULUS TESTS PERFORMED ON THE ASPHALT CONCRETE SPECIMENS

The values of resilient modulus can be used to evaluate the relative quality of materials as well as to generate input for pavement design or pavement evaluation and analysis.

5.8.1 Indirect Tension Test for Resilient Modulus of Asphalt Concrete Specimens

A review of the literature indicates that the modulus of resilience is the most common idealised modulus used in characterising asphalt mixtures. The modulus of resilience is defined as the ratio of applied stress to recoverable strain when a dynamic load is applied for a short loading time [65]. This modulus is determined by Indirect Tension Test Method according to ASTM D 4123-82. This method covers procedure for preparing and testing laboratory-fabricated specimens to determine resilient modulus values using the repeated -load indirect tension test. The procedure described covers a range of temperatures, loads, loading frequencies and load duration.

The repeated-load indirect tension test for determining resilient modulus of bituminous mixtures is conducted by applying compressive loads with a haversine or other suitable wave form. The load is applied vertically in the vertical diametrial plane of a cylindrical specimen of asphalt concrete. The resulting horizontal deformation of the specimen is measured and with an assumed Poisson's ratio, is used to calculate a resilient modulus (Figure 5.88)

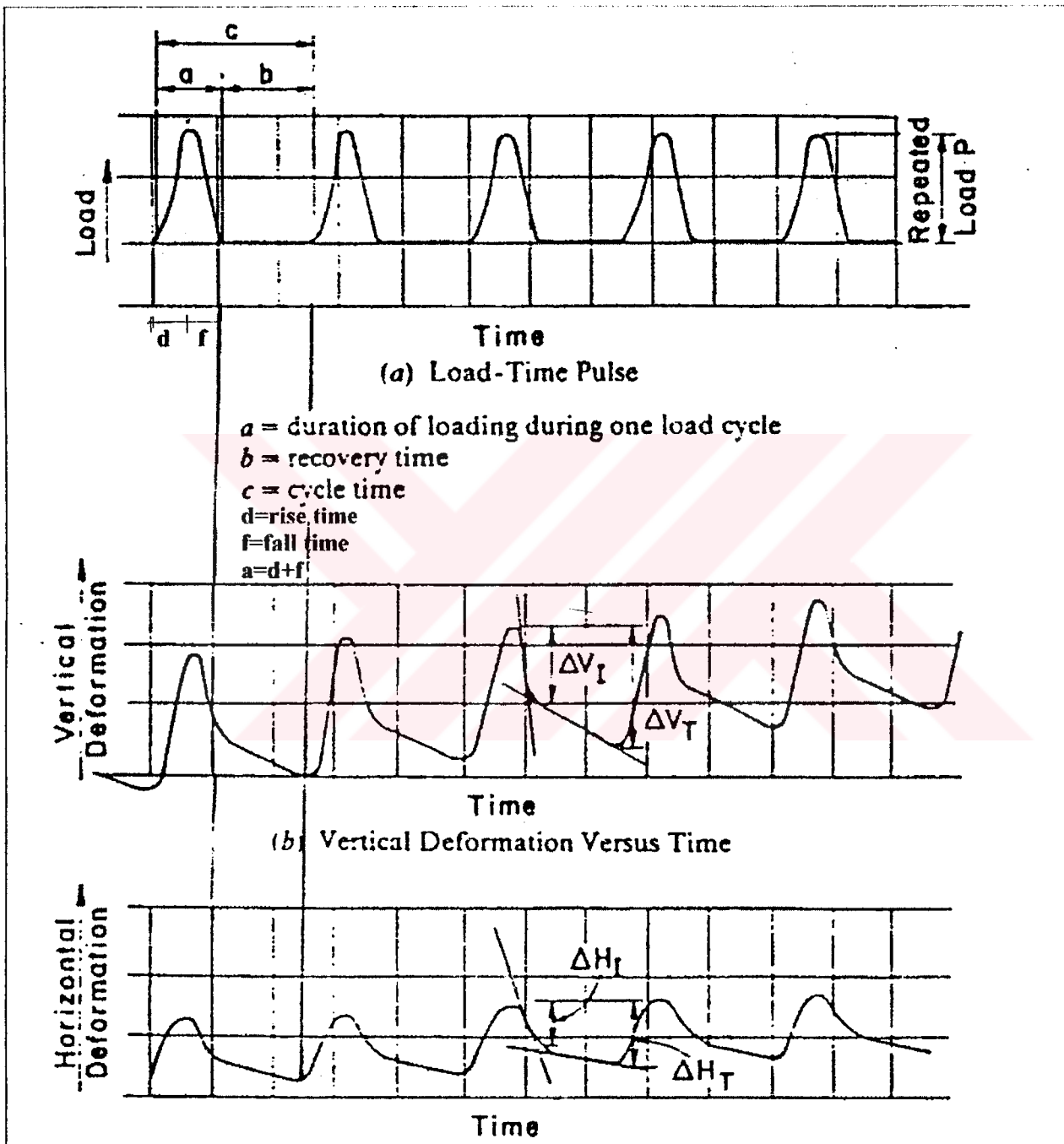


Figure 5.88 Typical Load and Deformation Versus Time Relationships for Repeated-Load Indirect Tension Test

5.8.2 Testing Device Used in This Investigation

Universal Materials Testing Apparatus (UMATTA) was used in this study (Figure 5.89). UMATTA provides researchers and engineers with a tool capable of conducting a range of tests on both bound and unbound materials. The system facilities recording and displaying of stress, strain and stiffness data of the specimen being tested and for extended periods of time or a number of loading cycles.

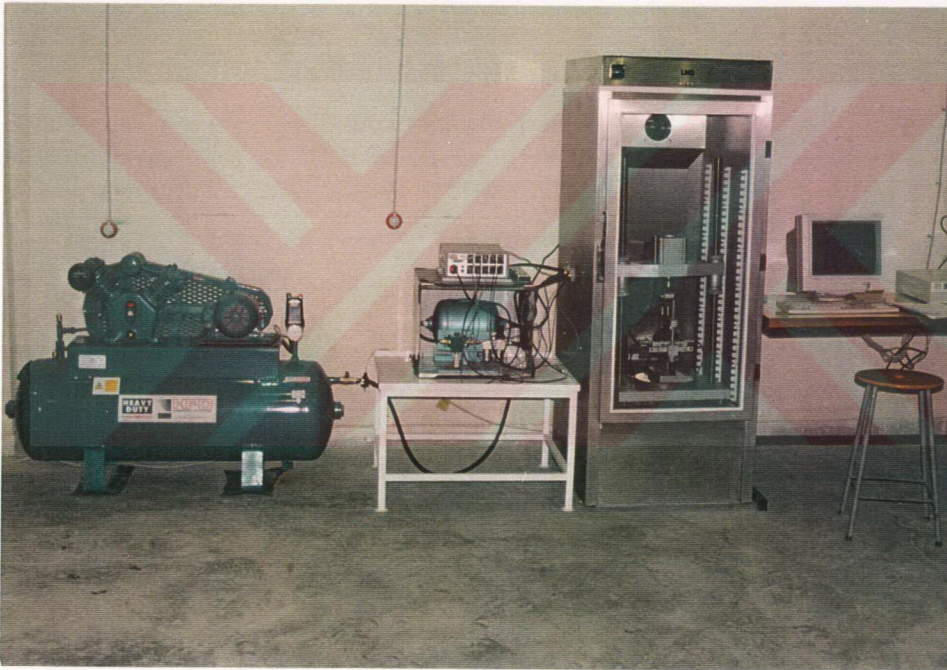


Figure 5.89 Universal Materials Testing Apparatus (UMATTA)

UMATTA comprises a Control and Data Acquisition System (CDAS), an IBM compatible personal computer (PC) and integrated software package. The CDAS captures and digitises analogue signals from a range of transducers then transfer these data to the PC for further processing via a standard communication link. Sufficient control and signal conditioning facilities are provided to enable dynamic control of axial load and measurement of the various transducer outputs.

The PC software is user friendly, menu driven and it has been written in Pascal. In operation, the system gathers the dynamic data from the transducers attached to the specimen under test then and provides real time of strain, modulus or wave form plots (as appropriate for each test type and function mode) on the screen.

5.8.2.1 The Indirect Tensile Jig

A jig is provided to allow mounting and loading of 100 mm and 150 mm diameter cylindrical asphalt specimens across a diameter. Loading platens machined to match the circumference of the specimen provide even distribution of load over a defined area. Sensitive displacement transducers are positioned on the transducer centre line by a yoke which is clamped to the specimen (Figure 5.90).

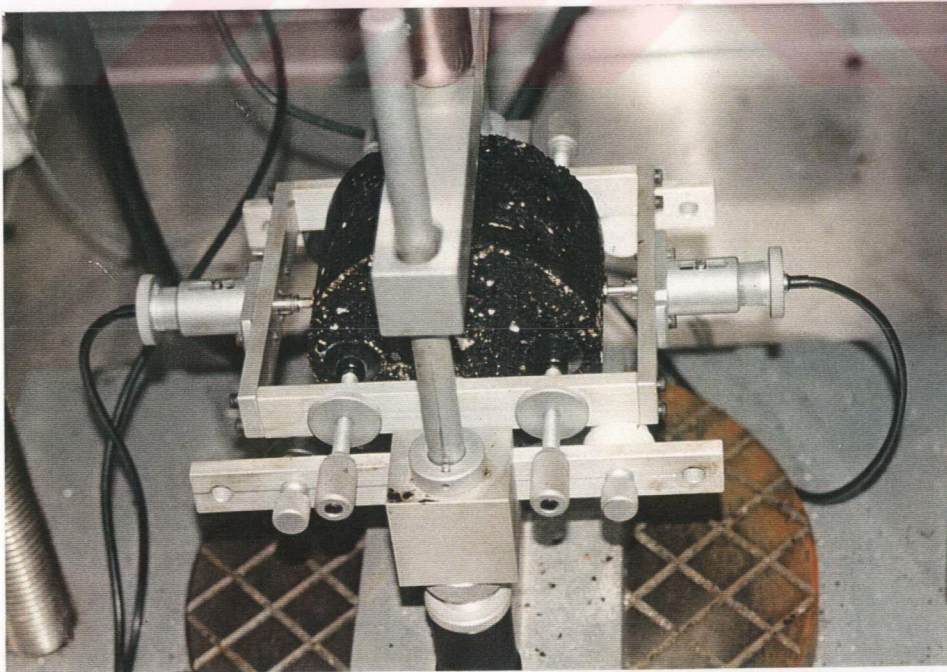


Figure 5.90 The Indirect Tensile Jig

5.8.2.2 The Temperature Chamber

A temperature chamber (Figure 5.91) is available from IPC for use in asphalt testing. The temperature range of the standard unit is from zero to 60 degrees Celcius.

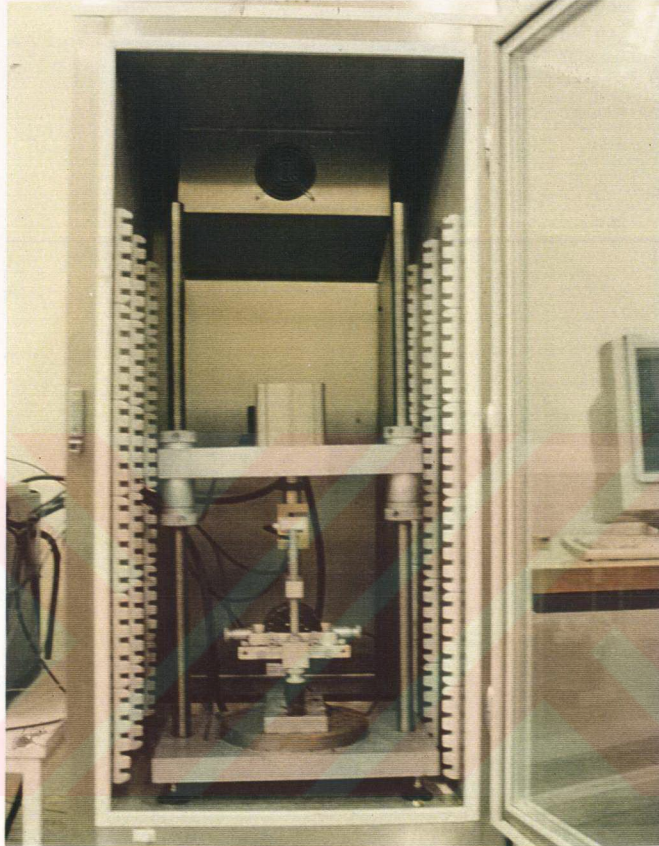


Figure 5.91 Temperature chamber which has a range from 0 to 60°C for use in asphalt testing.

5.8.3 The Variables Used in The Resilient Modulus Test

There are many variables affecting the resilient modulus of an asphalt concrete specimen. They are load magnitude, load duration, test temperature, loading frequency. Load duration is the most important variable and it is recommended that the duration be held to some minimum which can be recorded. The recommended time for the load duration is 0.1 to 0.4 seconds, with *0.1 second being more representative of transient pavement loading* [65] Recommended frequencies are 0.33, 0.5 and 1 Hz.

Since the procedure is non-destructive, tests in the different temperatures and rise time values can be repeated on the same specimen. Specimens subjected to Marshall and Resilient modulus test are presented in Figure 5.92



Figure 5.92 Specimens prepared for marshall and resilient modulus tests

Applied Load : 650 N (For each of the selected rise time value, the UMATTA software assigned the different load range. Since the test device capacity supported min 650 N for all selected rise time values, this value has been selected)

Loading Frequency : 1 Hz (Pulse Repetition Period). Recommended frequencies are 0.33, 0.5, and 1 Hz.

Loading Time : Rise Time + Fall Time load duration is the more important variable and it is recommended that the duration be held to some minimum which can be recorded. (UMATTA Software Supports only the rise time)

Rise Time : 30 - 60 and 100 ms (The recommended time for the load duration is to 0.4 s, with 0.1 s being more representative of transient pavement loading) (Device capacity is 30-130 ms)

Test Temperature : 5 - 25 - 40 and 60°C (Device capacity 0-60°C)

5.8.4 Test Procedure for Resilient Modulus

The procedure for the resilient modulus test consists of the following:

5 load repetitions were applied to the specimens because the resilient deformation become stable after 5 load pulses. Since the resilient modulus test was performed on the Marshall test specimens, after they had been prepared according to ASTM D 1559. The measurements made on the Marshall test specimen are given in Appendix C.

1. The test specimens were cured at room temperature for 24 hours before testing.
2. The test specimens were kept in the temperature control chamber for at least four hours to bring them to the required temperature. The dummy specimen was also placed in the temperature control chamber to monitor the temperature before and during testing.
3. The specimen, selected at random, was placed in the test stand to mount the transducer yoke, and a horizontal line was marked on the specimen to indicate the position of the LVDT s. Then the LVDT yoke was mounted and the specimen was placed in the loading frame of the resilient test equipment, inside the temperature control chamber. The yoke was then aligned to keep the LVDT s in a horizontal position a conditioning loading of 10 lb. was applied to hold the specimen in place.
4. Before the actual deformation was measured, the specimen was conditioned through application of a repetitive, 5 pulse load.

5. The LVDT's adjustment screw was turned to bring the LVDT's probe tips in contact with the specimen.
6. After the conditioning loading, it was observed that the resilient horizontal deformation was stable. Hence, resilient modulus tests were performed at five cycles. The horizontal deformation was recorded until the resilient (recoverable) strain became stable.
7. After the deformation was recorded, the pulse was stopped and the specimen was rotated 90 degrees and tested again, using the same procedure as describe in steps 3 through 6.
8. Steps 3 through 7 were repeated using new specimens. Three specimens were tested for each binder content.
9. Steps 1 through 8 were repeated using four different test temperatures.

The Resilient modulus values and total recoverable resilient strain measurements are given in Appendix B.

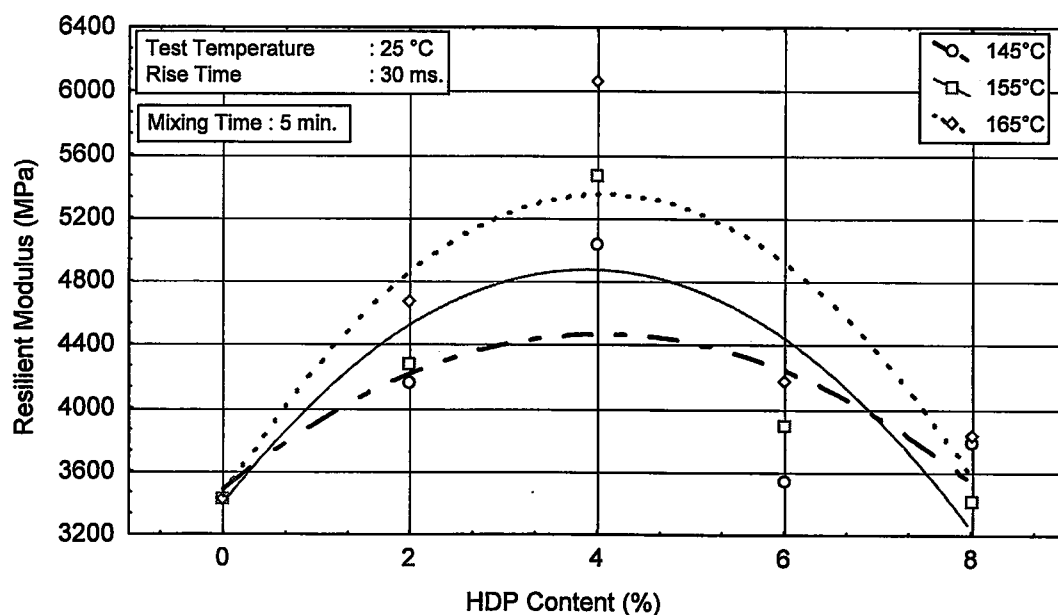


Figure 5.93 Variation of resilient modulus with polyethylene content for 5 minute mixing time, specimens tested at 25°C and 30 ms rise time

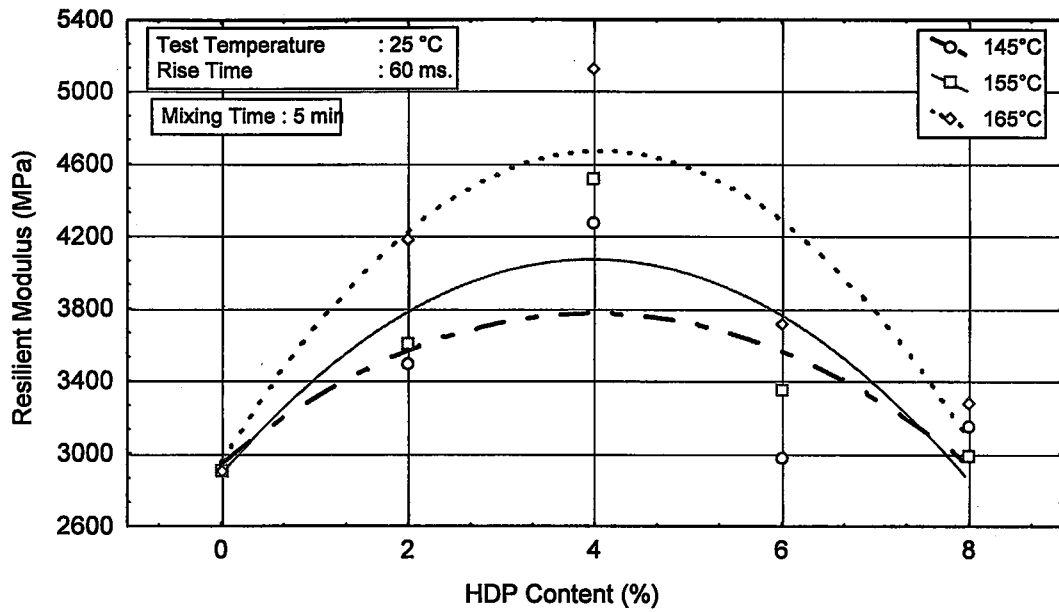


Figure 5.94 Variation of resilient modulus with polyethylene content for 5 minute mixing time, specimens tested at 25°C and 60 ms rise time

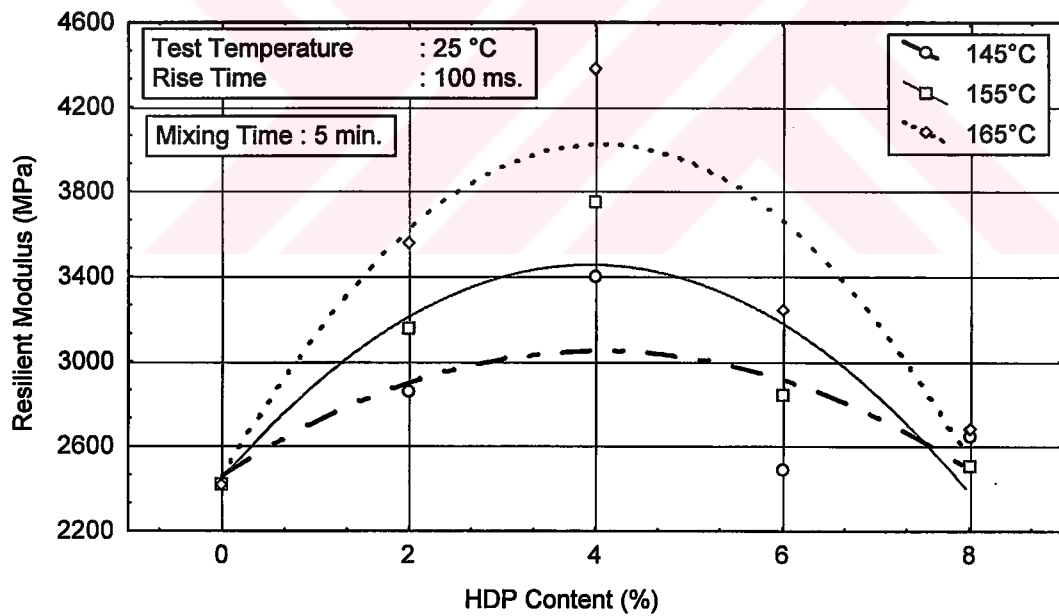


Figure 5.95 Variation of resilient modulus with polyethylene content for 5 minute mixing time, specimens tested at 25°C and 100 ms rise time

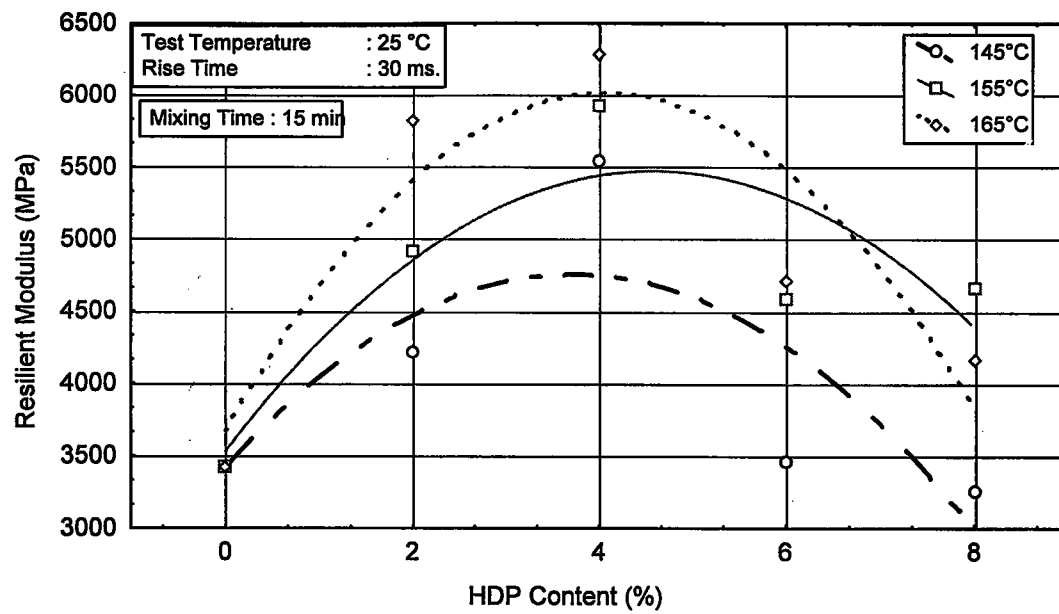


Figure 5.96 Variation of resilient modulus with polyethylene content for 15 minute mixing time, specimens tested at 25°C and 30 ms rise time

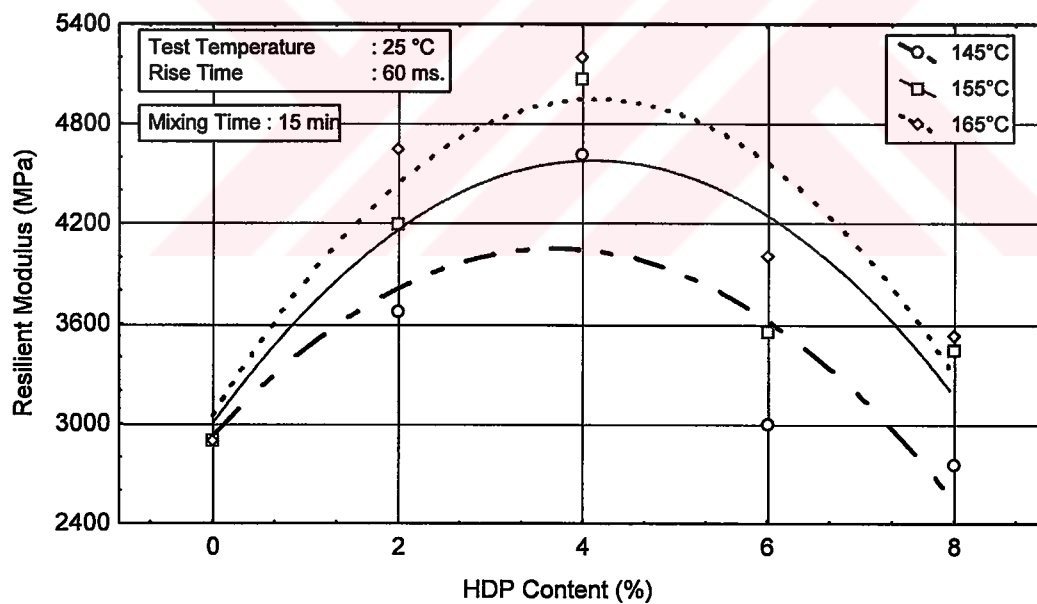


Figure 5.97 Variation of resilient modulus with polyethylene content for 15 minute mixing time, specimens tested at 25°C and 60 ms rise time

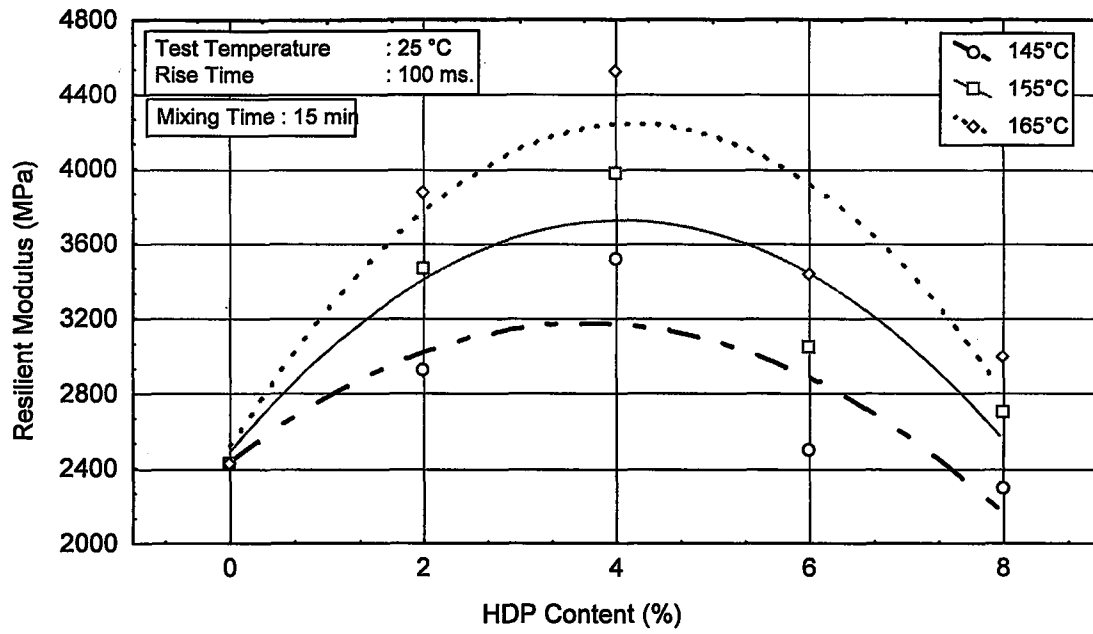


Figure 5.98 Variation of resilient modulus with polyethylene content for 15 minute mixing time, specimens tested at 25°C and 100 ms rise time

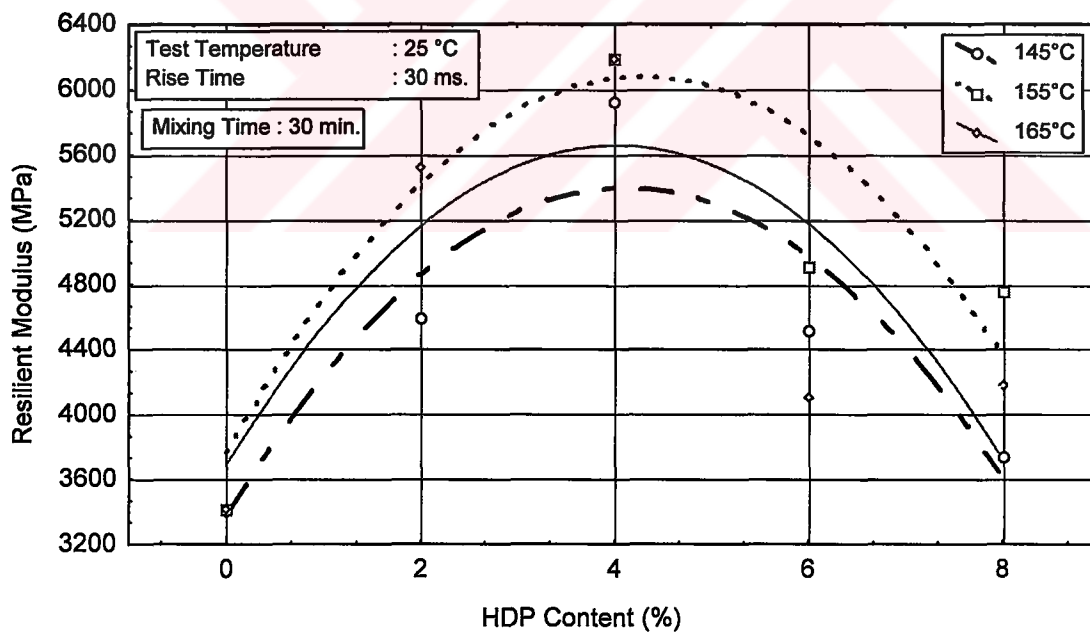


Figure 5.99 Variation of resilient modulus with polyethylene content for 30 minute mixing time, specimens tested at 25°C and 30 ms rise time

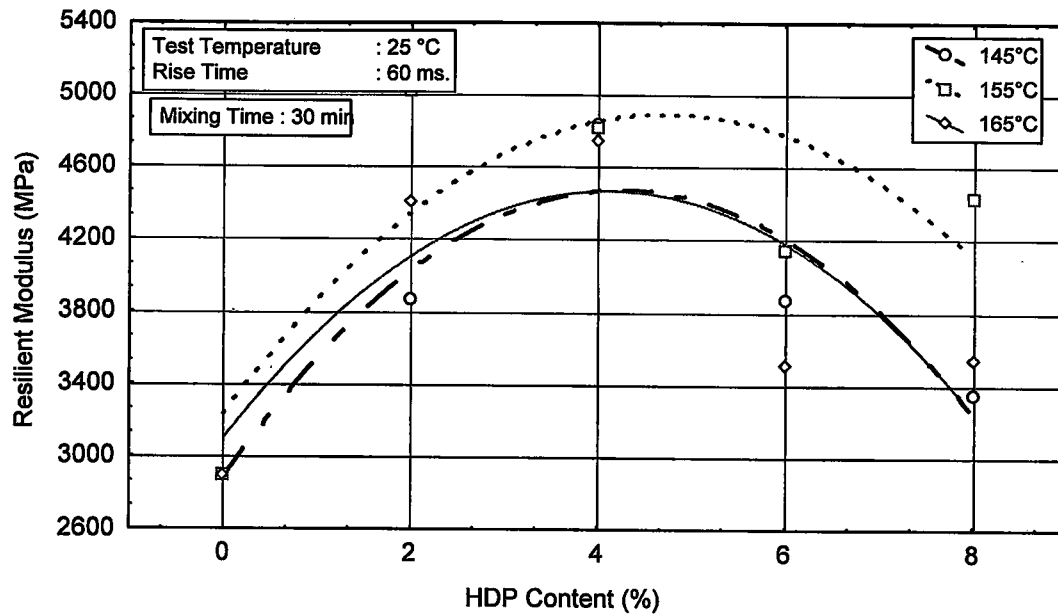


Figure 5.100 Variation of resilient modulus with polyethylene content for 30 minute mixing time, specimens tested at 25°C and 60 ms rise time.

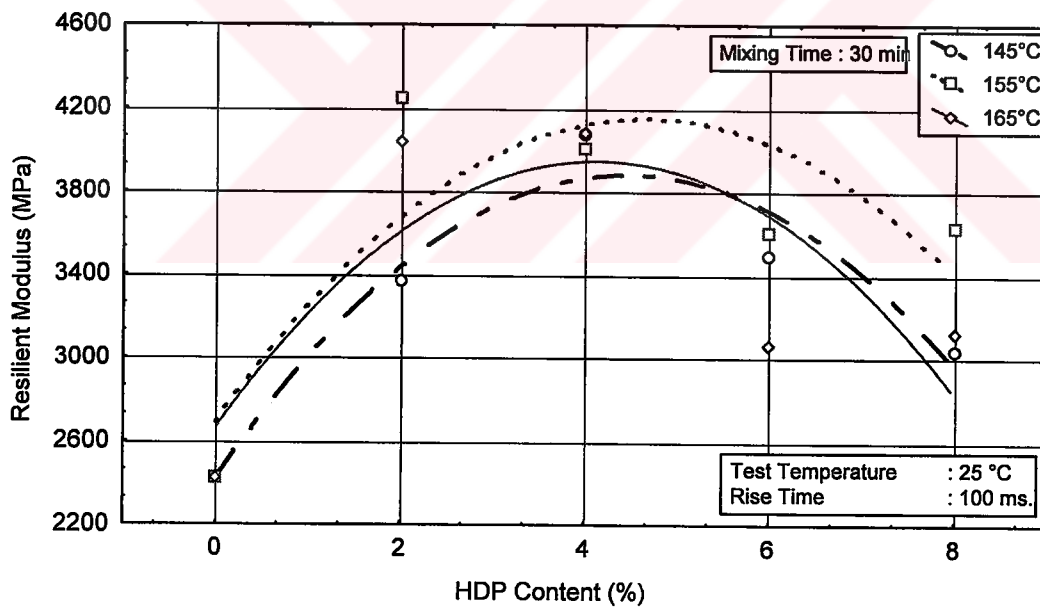


Figure 5.101 Variation of resilient modulus with polyethylene content for 30 minute mixing time, specimens tested at 25°C and 100 ms rise time

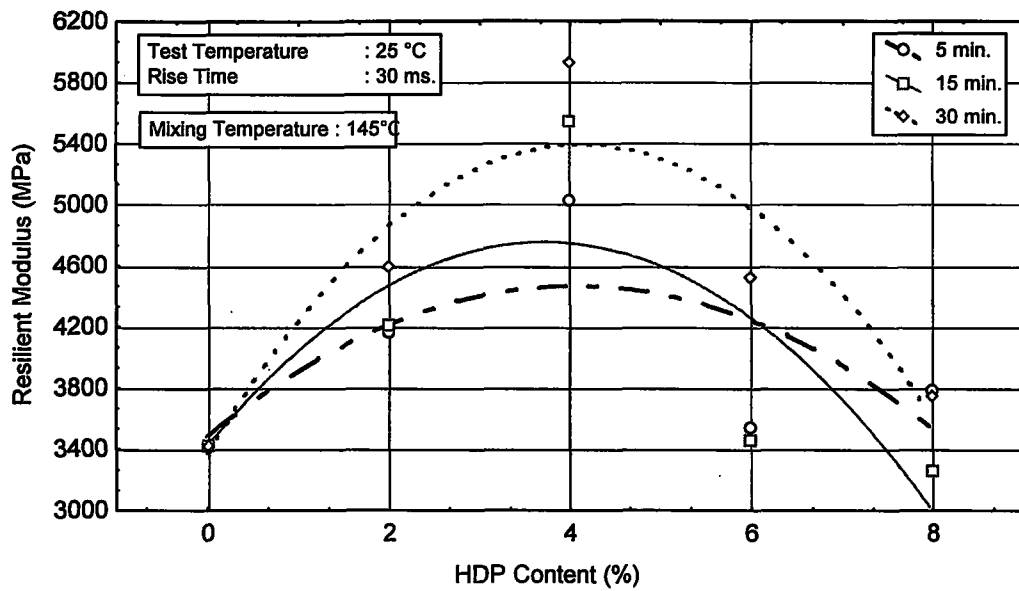


Figure 5.102 Variation of resilient modulus with polyethylene content for 145°C mixing temp, specimens tested at 25°C and 30 ms rise time

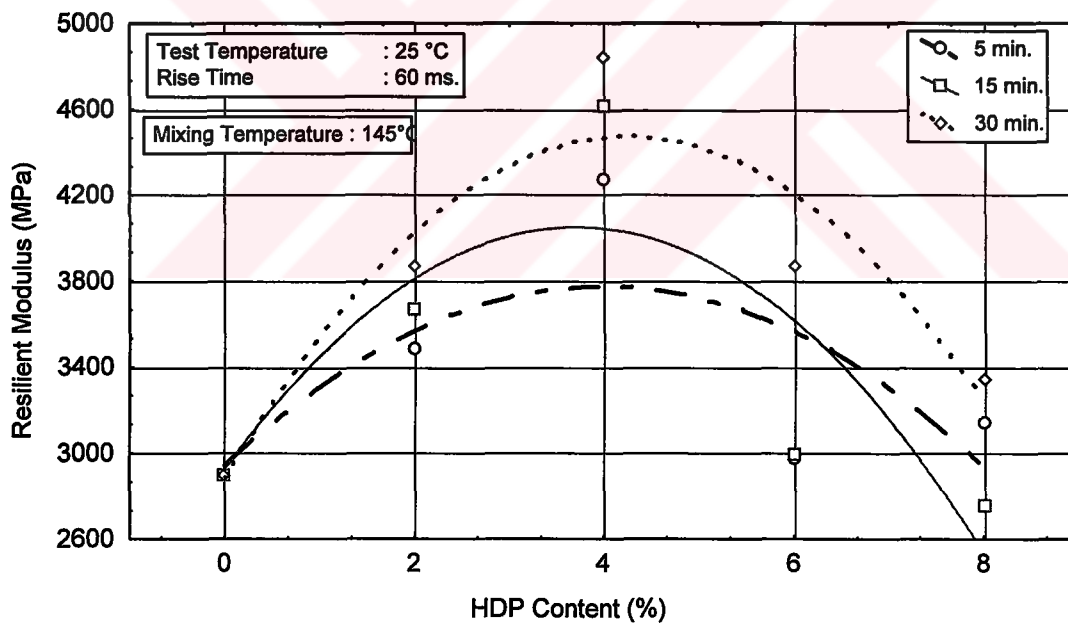


Figure 5.103 Variation of resilient modulus with polyethylene content for 145°C mixing temp, specimens tested at 5°C and 60 ms rise time

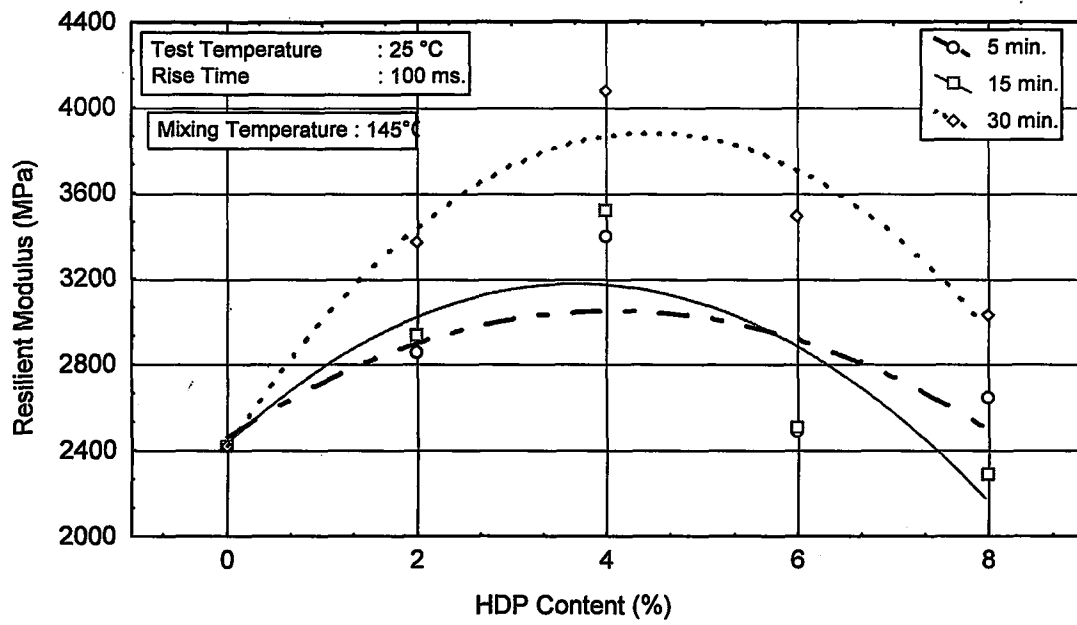


Figure 5.104 Variation of resilient modulus with polyethylene content for 145°C mixing temp, tested specimens at 25°C and 100 ms rise time

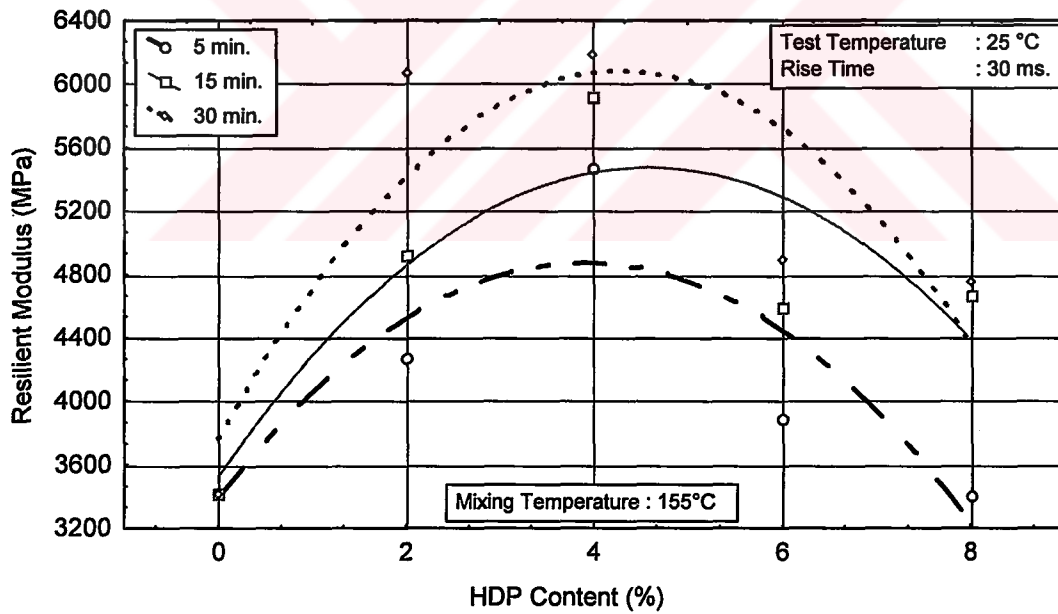


Figure 5.105 Variation of resilient modulus with polyethylene content for 155°C mixing temp, specimens tested at 25°C and 30 ms rise time

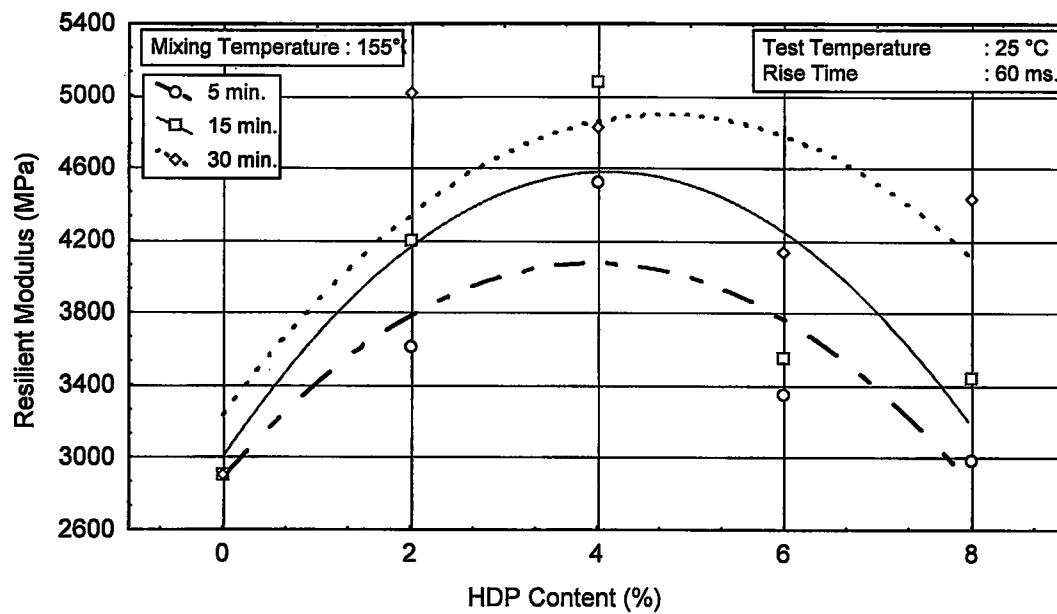


Figure 5.106 Variation of resilient modulus with polyethylene content for 155°C mixing temp, specimens tested at 25°C and 60 ms rise time

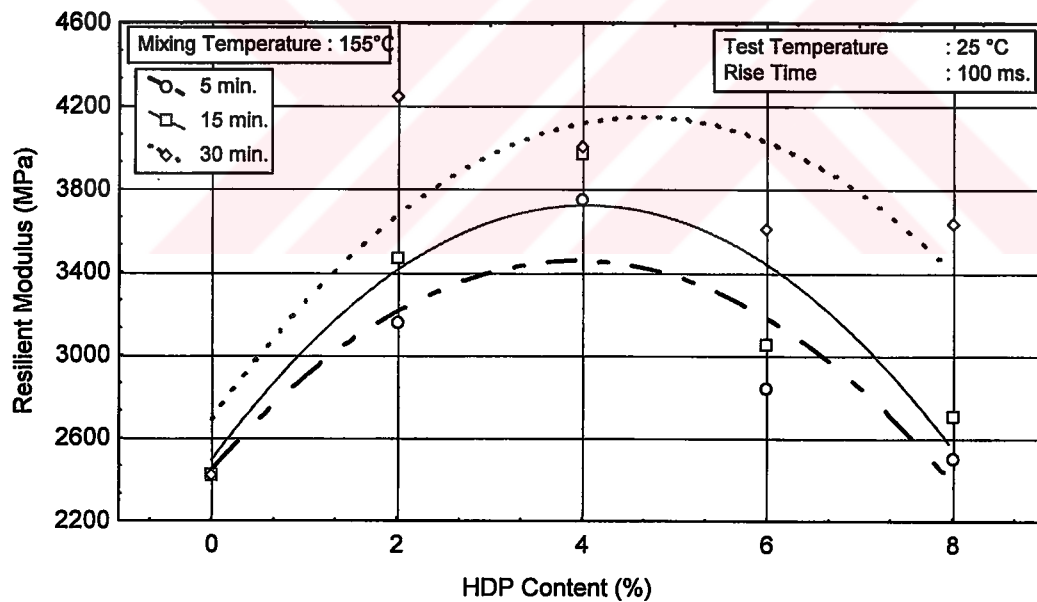


Figure 5.107 Variation of resilient modulus with polyethylene content for 155°C mixing temp, specimens tested at 25°C and 100 ms rise time

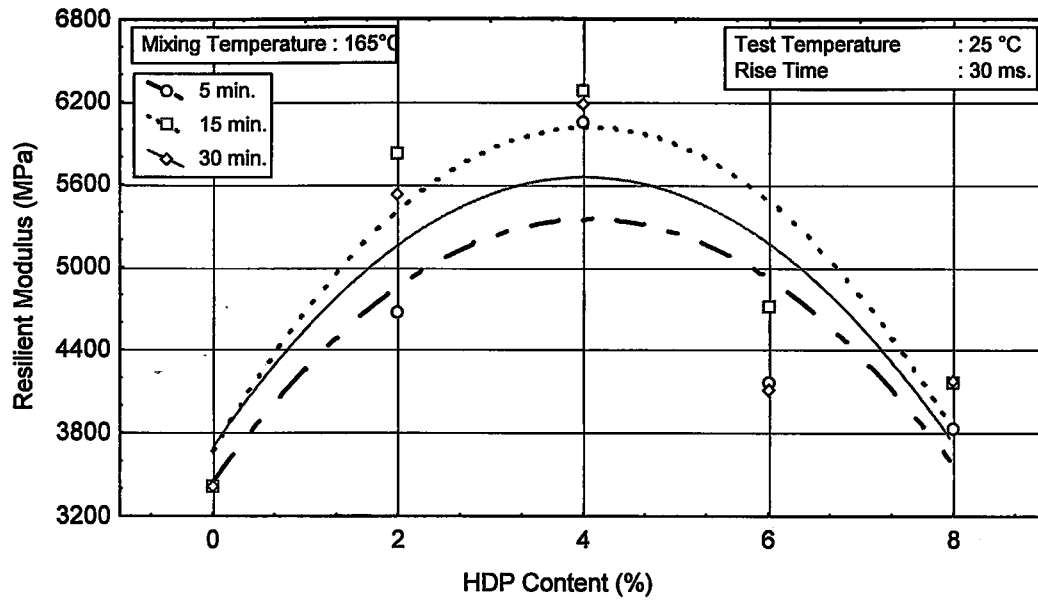


Figure 5.108 Variation of resilient modulus with polyethylene content for 165°C mixing temp, specimens tested at 25°C and 30 ms rise time

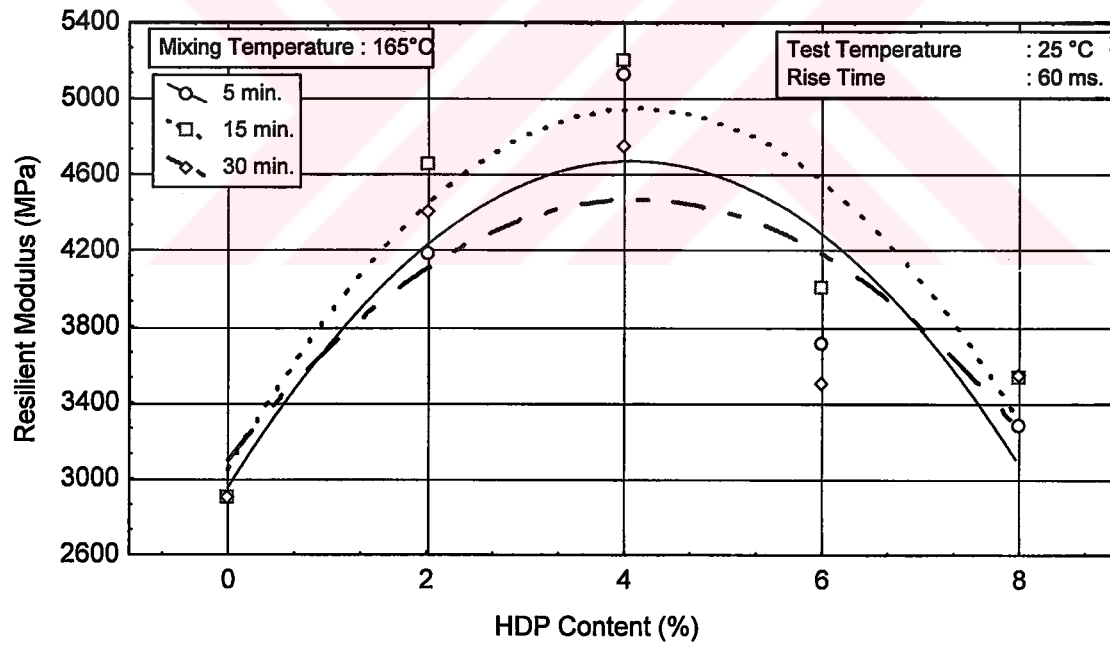


Figure 5.109 Variation of resilient modulus with polyethylene content for 165°C mixing temp, specimens tested at 5°C and 60 ms rise time

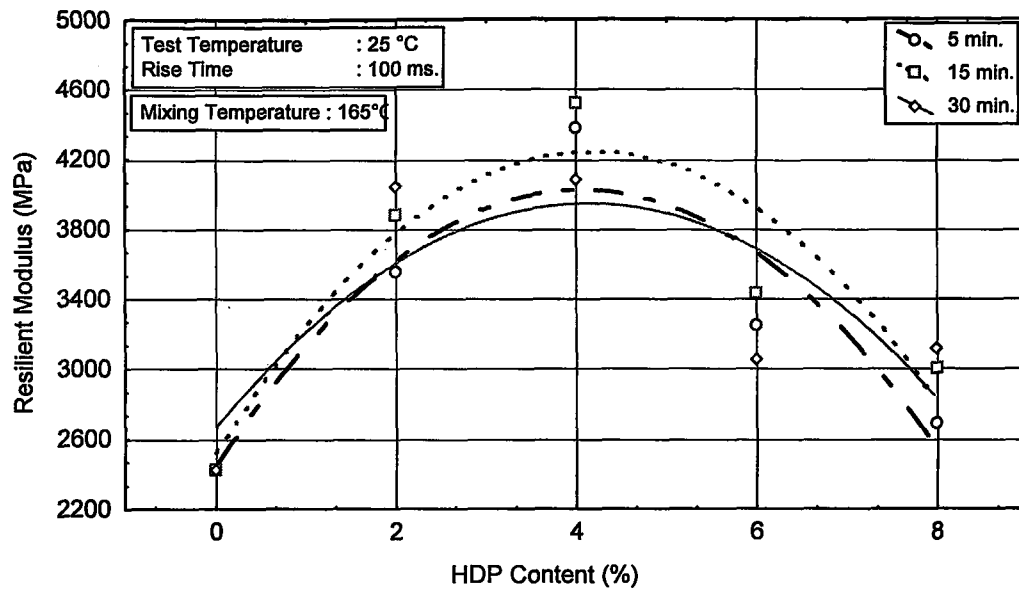


Figure 5.110 Variation of resilient modulus with polyethylene content for 165°C mixing temp, specimens tested at 25°C and 100 ms rise time

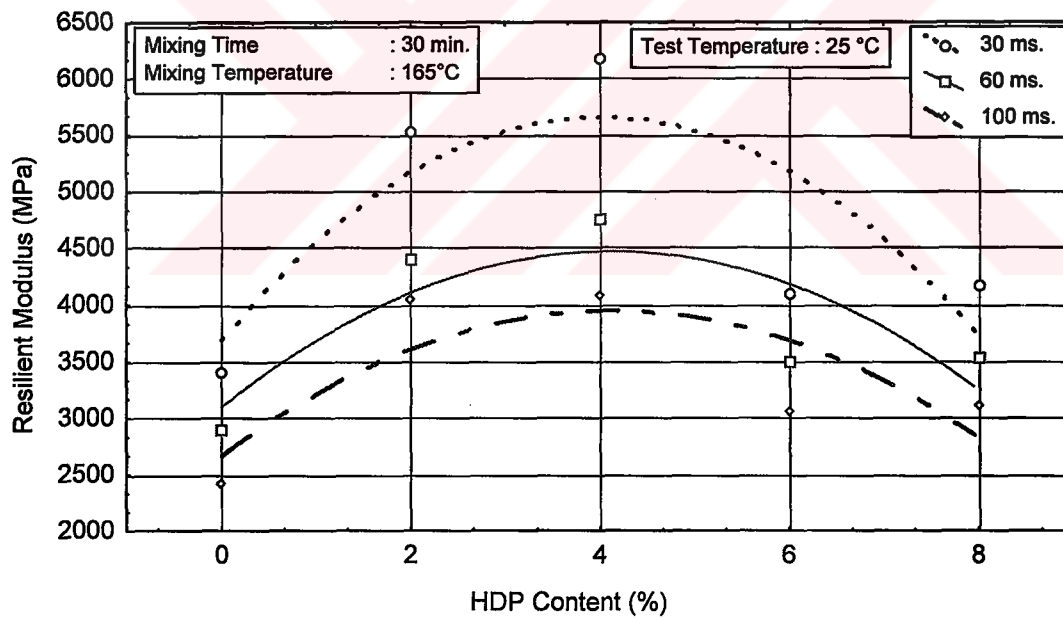


Figure 5.111 Variation of resilient modulus with polyethylene content for 30 minute mixing time and 165°C mixing temp, specimens tested at 25°C.

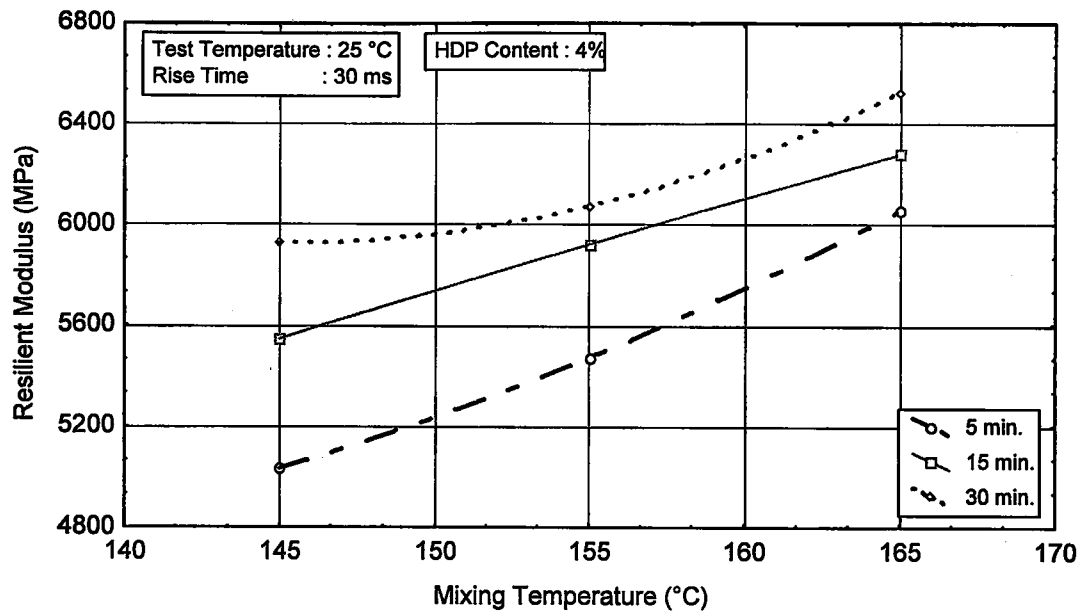


Figure 5.112 Variation of resilient modulus with mixing temperature for 4%HDP content, specimens tested at 25°C and 30 ms rise time.

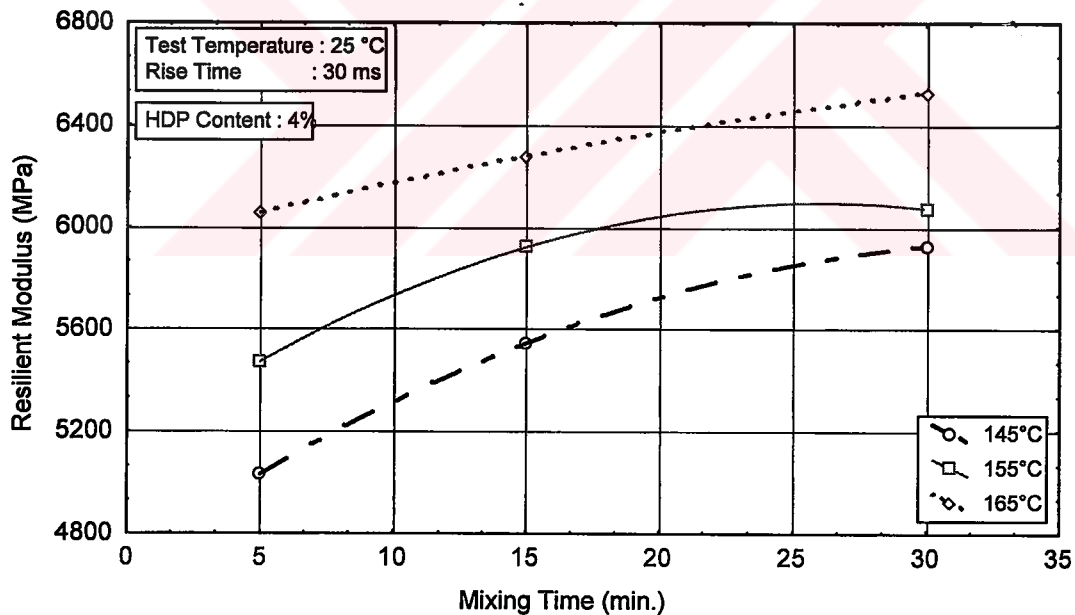


Figure 5.113 Variation of resilient modulus with mixing time for 4% HDP content, specimens tested at 25°C and 30 ms rise time

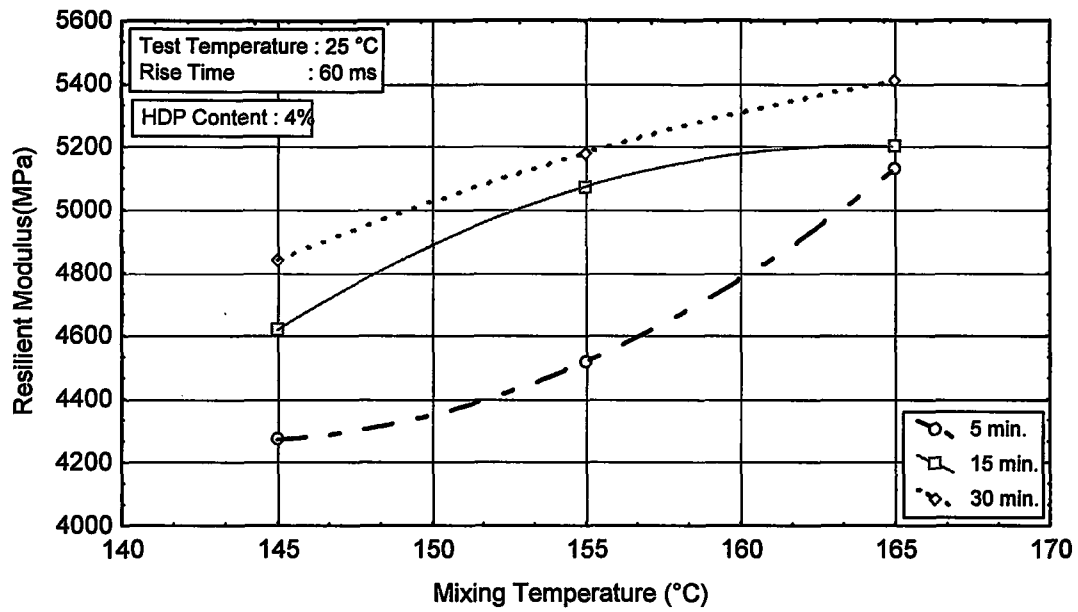


Figure 5.114 Variation of resilient modulus with mixing temperature for 4% HDP content , specimens tested at 25°C and 60 ms rise time.

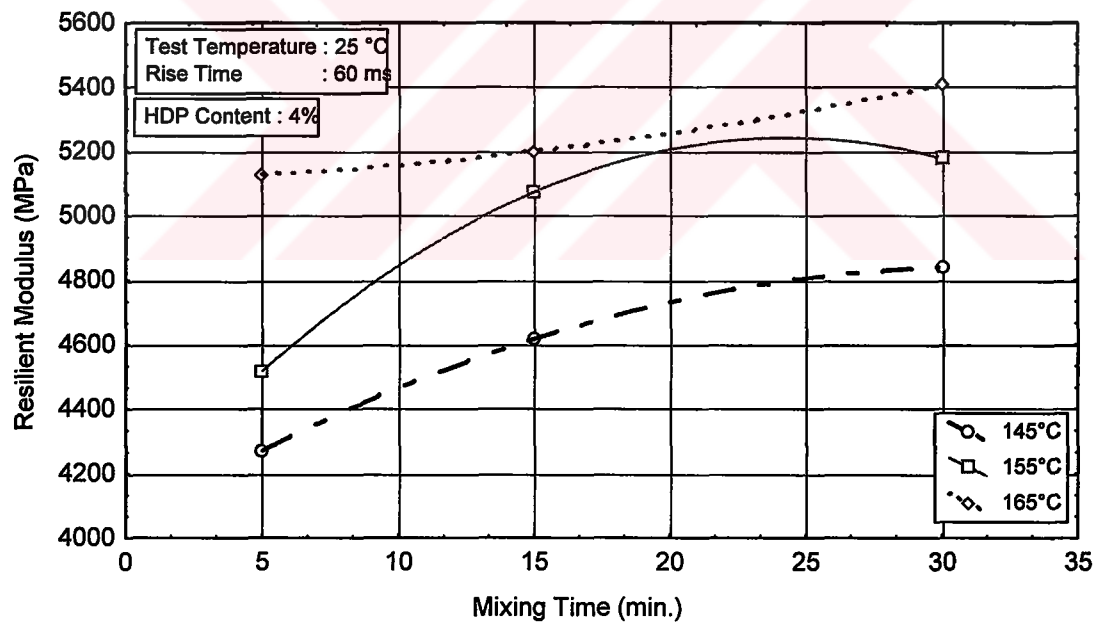


Figure 5.115 Variation of resilient modulus with mixing time for 4% HDP content , specimens tested at 25°C and 60 ms rise time.

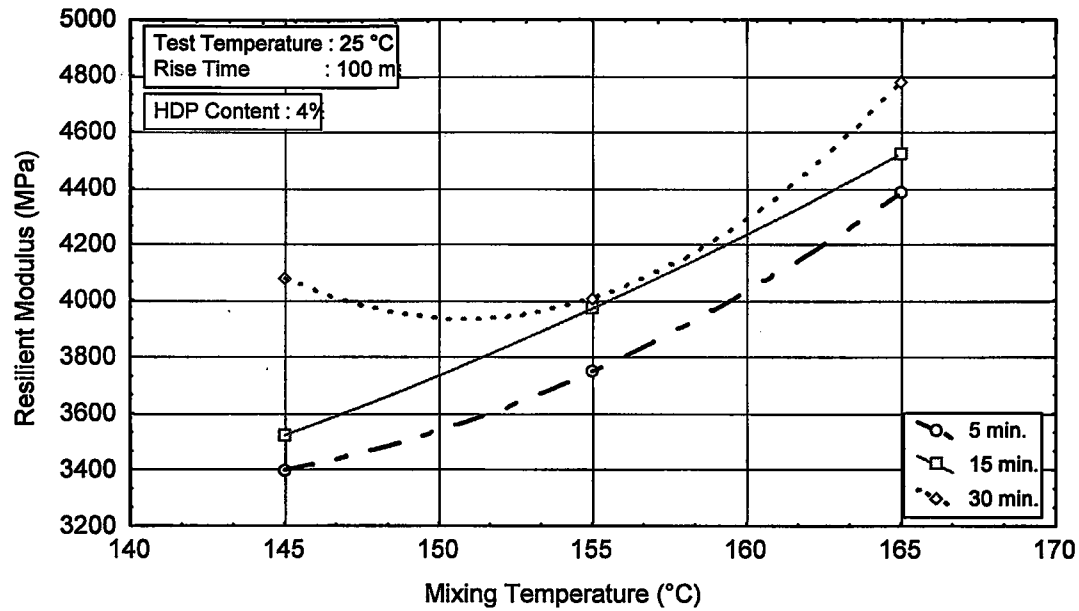


Figure 5.116 Variation of resilient modulus with mixing temperature for 4% HDP content, specimens tested at 25°C and 100 ms rise time.

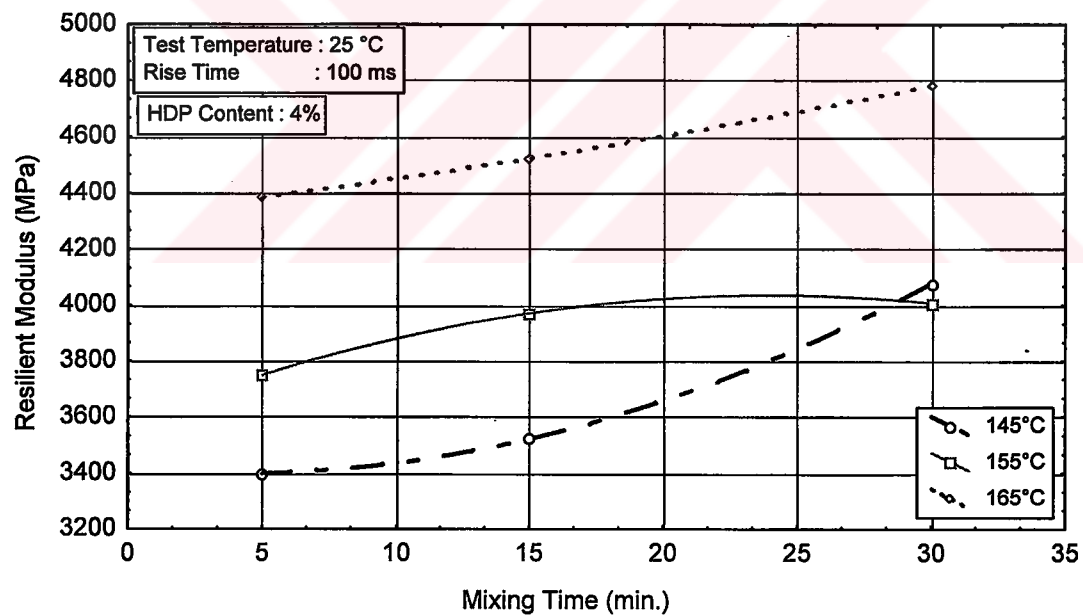


Figure 5.117 Variation of resilient modulus with mixing time for 4% HDP content, specimens tested at 25°C and 100 ms rise time.

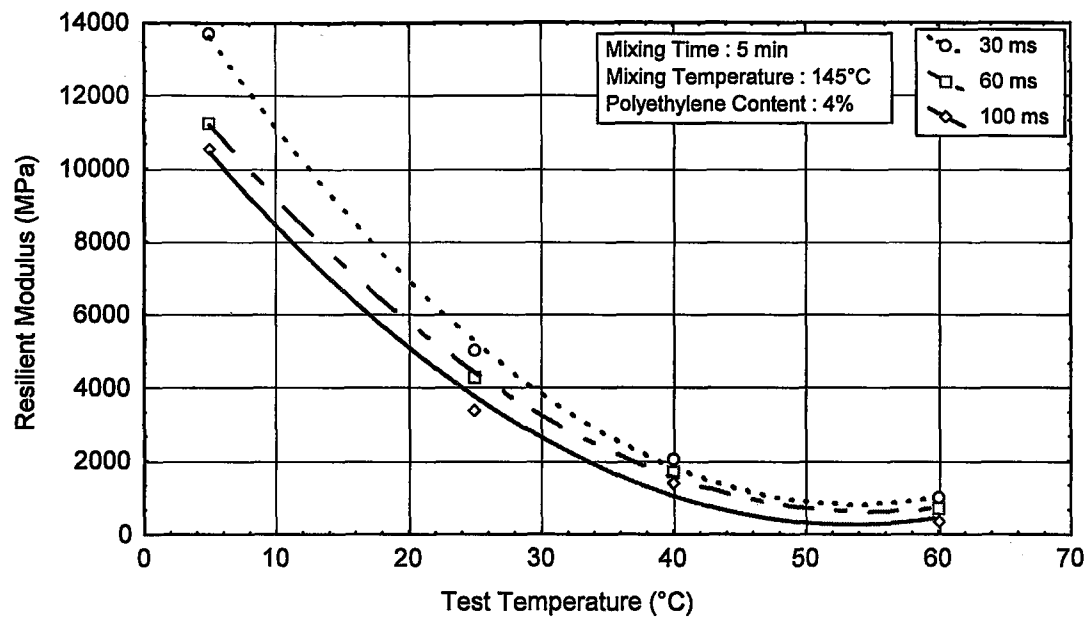


Figure 5.118 Variation of resilient modulus with test temperature for 5 minute mixing time and 145°C mixing temp. (specimens contained 4% polyethylene)

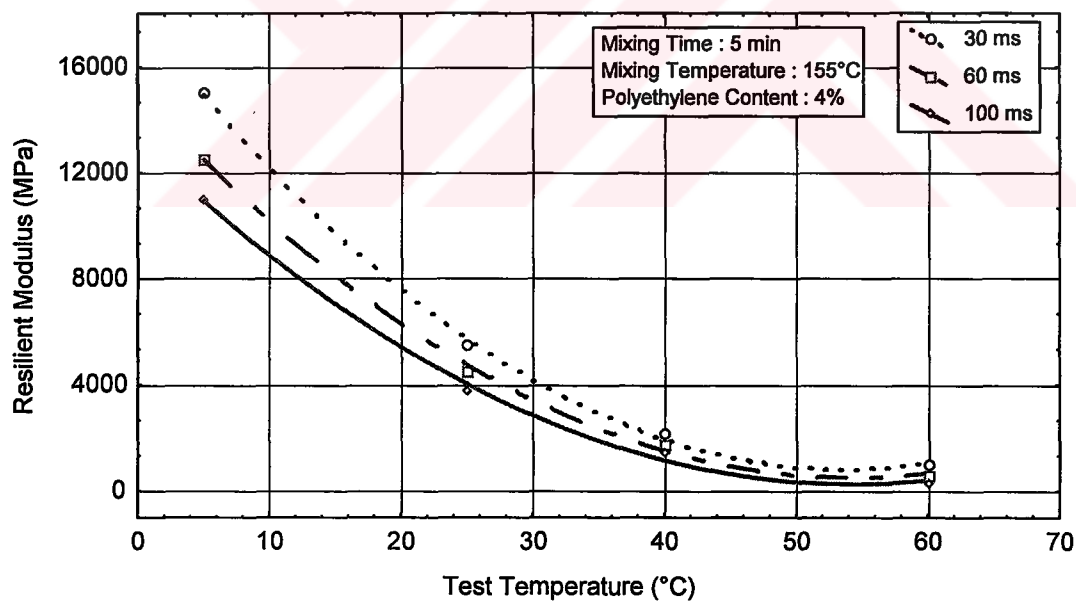


Figure 5.119 Variation of resilient modulus with test temperature for 5 minute mixing time and 155°C mixing temp. (specimens contained 4% polyethylene)

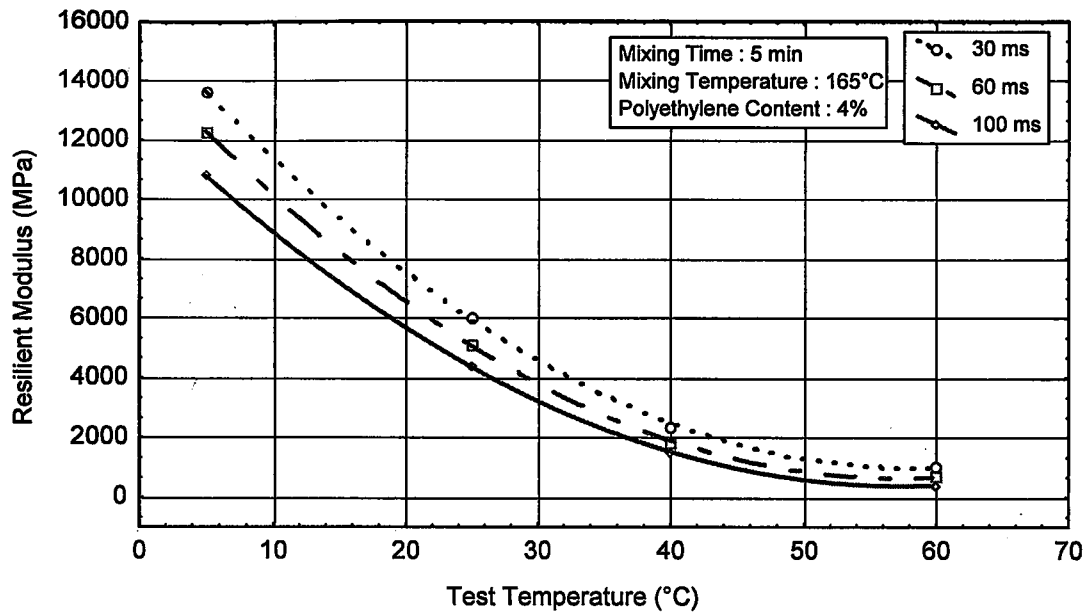


Figure 5.120 Variation of resilient modulus with test temperature for 5 minute mixing time and 165°C mixing temp. (specimens contained 4% polyethylene)

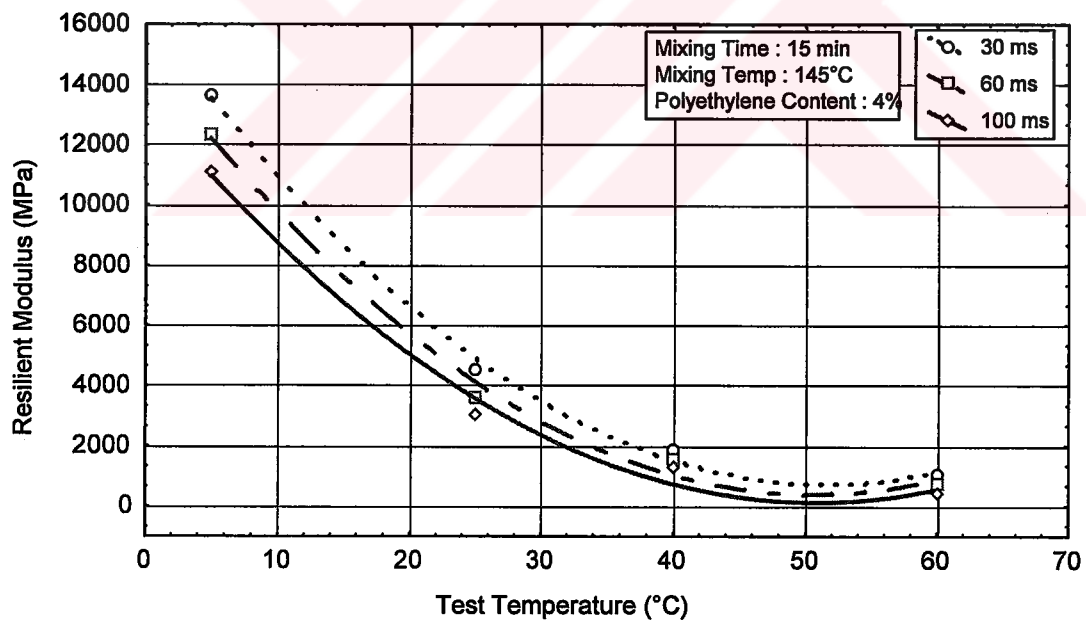


Figure 5.121 Variation of resilient modulus with test temperature for 15 minute mixing time and 145°C mixing temp. (specimens contained 4% polyethylene)

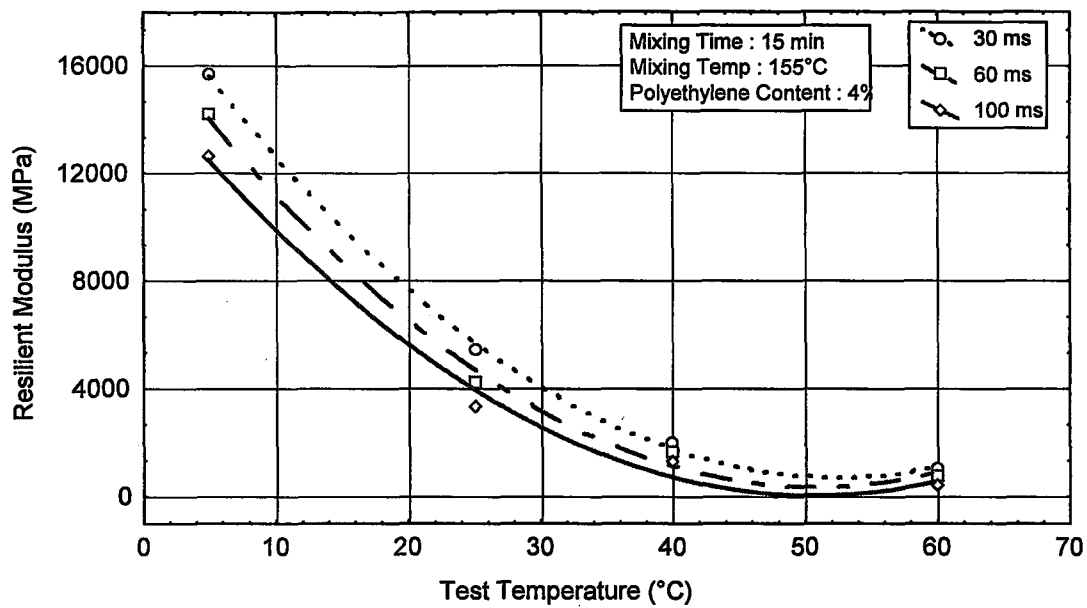


Figure 5.122 Variation of resilient modulus with test temperature for 15 minute mixing time and 155°C mixing temp. (specimens contained 4% polyethylene)

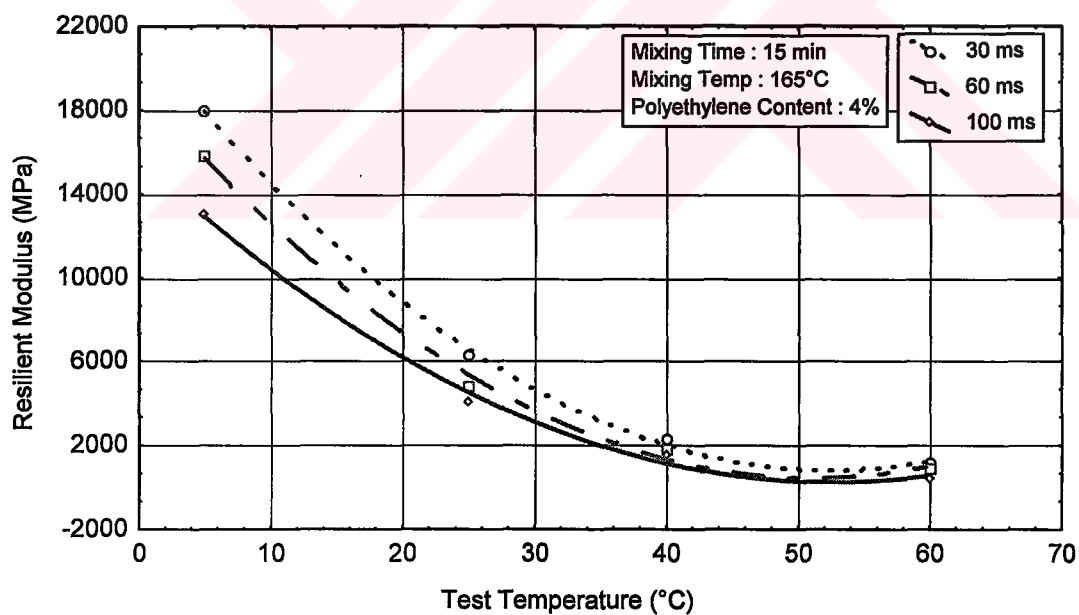


Figure 5.123 Variation of resilient modulus with test temperature for 15 minute mixing time and 165°C mixing temp. (specimens contained 4% polyethylene)

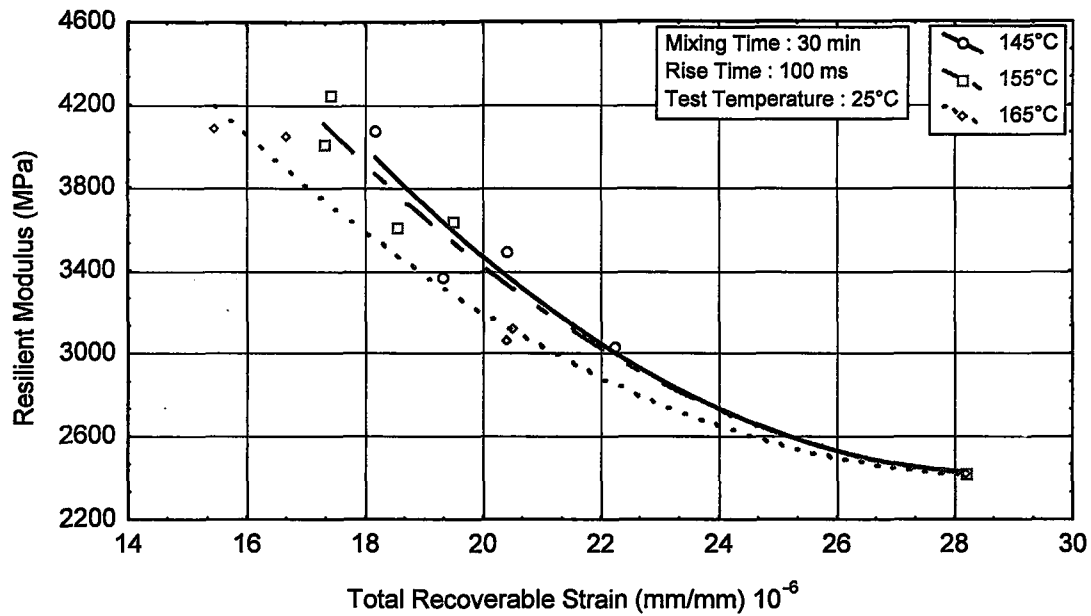


Figure 5.124 Variation of resilient modulus with test temperature for 30 minute mixing time, specimens tested at 25°C and 100 ms rise time (specimens contained 4% polyethylene)

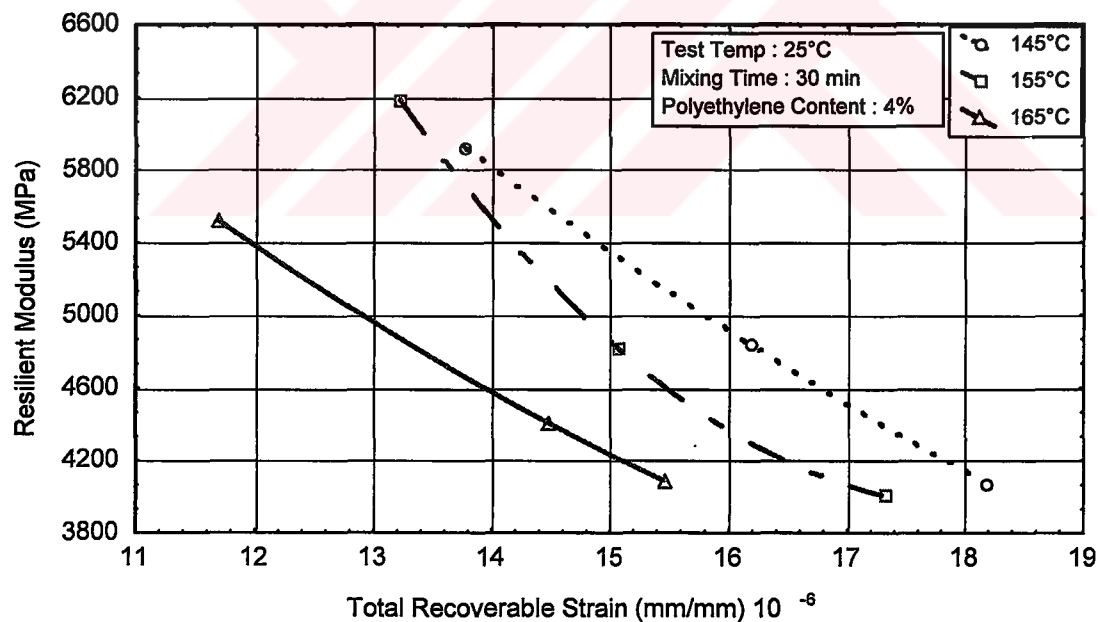


Figure 5.125 Variation of resilient modulus with test temperature for 30 minute mixing time, specimens tested at 25°C (specimens contained 4% polyethylene)

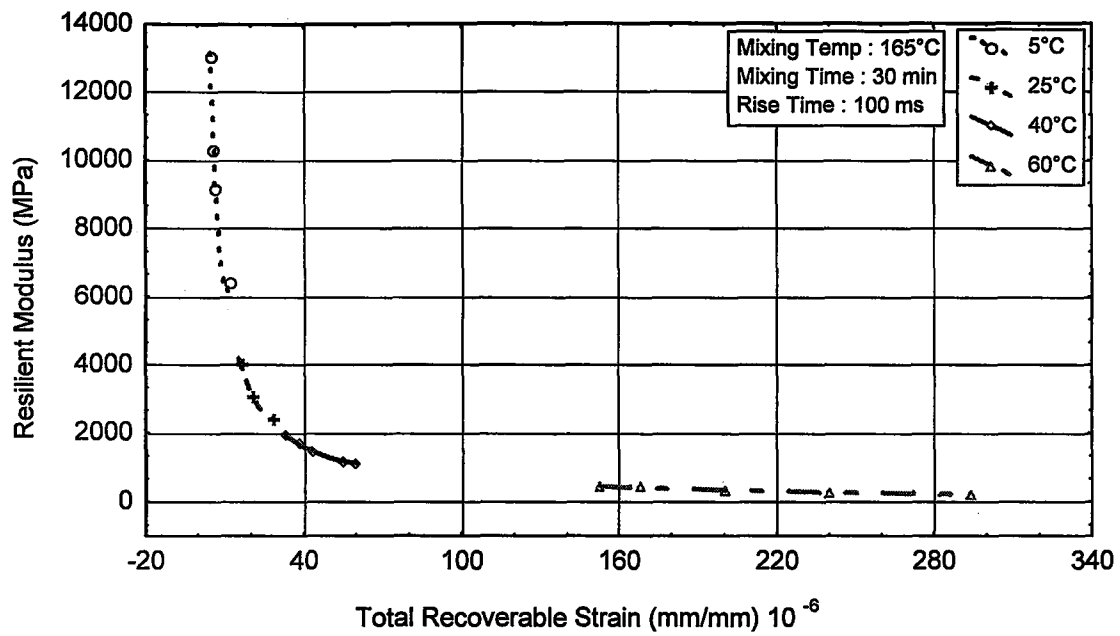


Figure 5.126 Variation of resilient modulus with test temperature for 165°C mixing temp and 30 minute mixing time, specimens tested at 100 ms rise time (specimens contained 4% polyethylene)

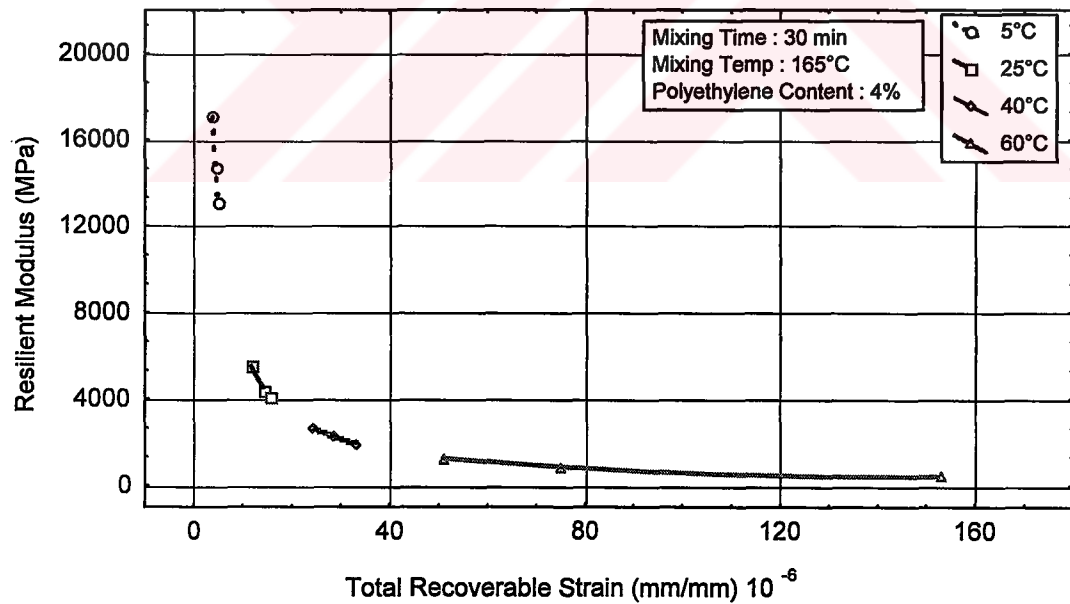


Figure 5.127 Variation of resilient modulus with test temperature for 165°C mixing temp and 30 minute mixing time, specimens tested at 100 ms rise time (specimens contained 4% polyethylene)

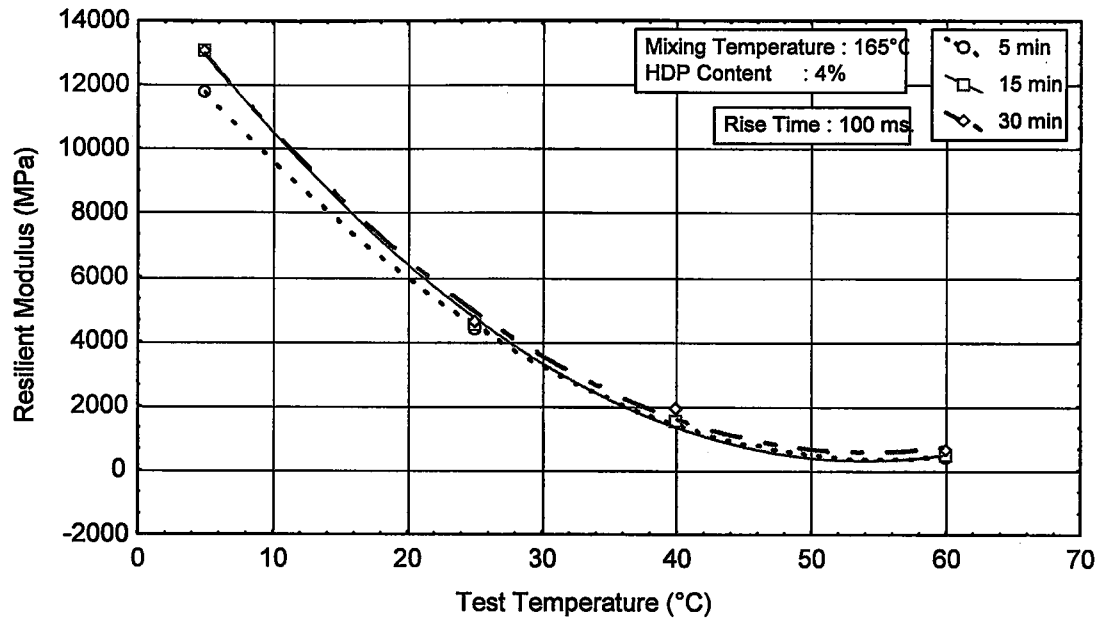


Figure 5.128 Variation of resilient modulus with test temperature for 165°C mixing temp, specimens tested at 100 ms rise time (specimens contained 4% polyethylene)

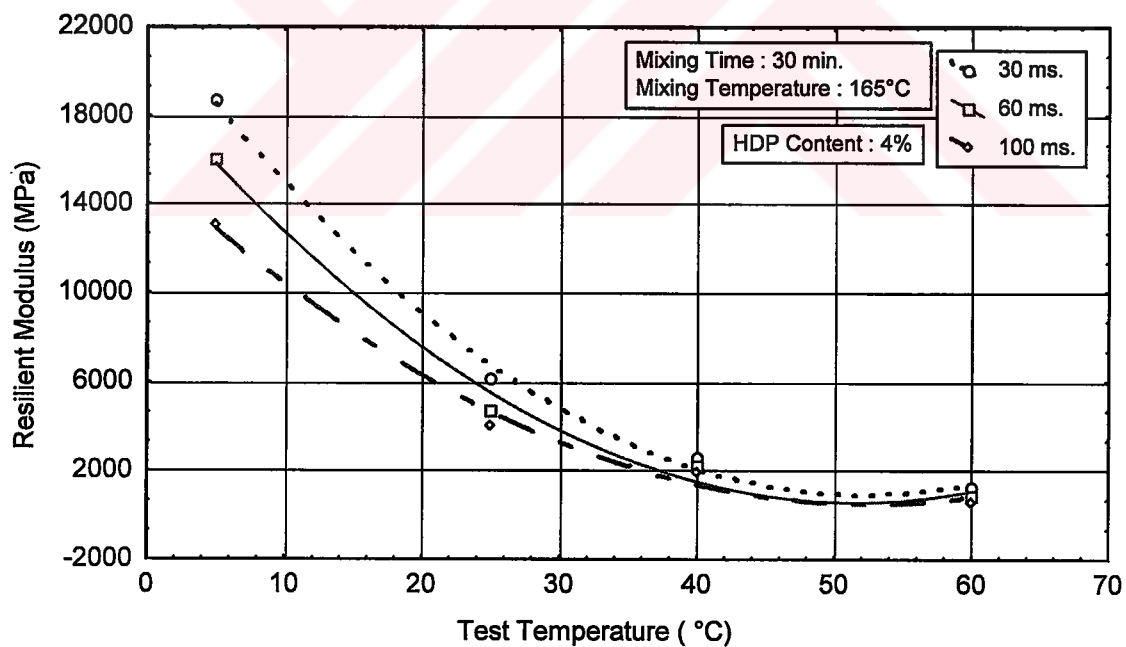


Figure 5.129 Variation of resilient modulus with test temperature for 165°C mixing temp and 30 minute mixing time, (specimens contained 4% polyethylene)

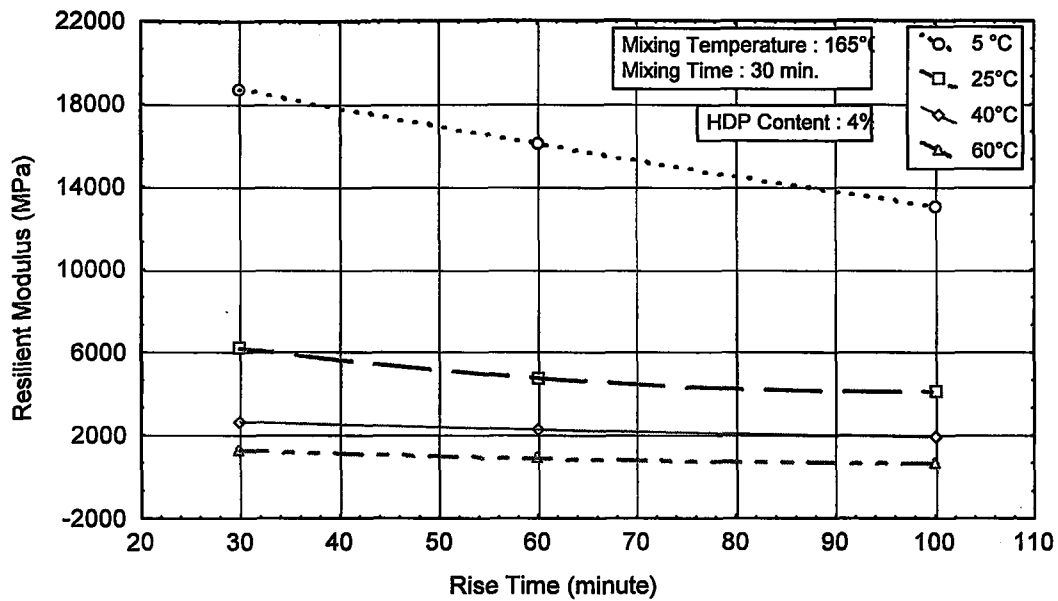


Figure 5. 130 Variation of resilient modulus with rise time for 165°C mixing temp and 30 minute mixing time (specimens contained 4% polyethylene)

All the Figures pertaining to the Resilient Modulus shows the variation of Resilient Modulus with HDP content, mixing temperature and the mixing time. The maximum Resilient Modulus is reached at 165°C with 4% HDP content for 30 minute mixing time. At all mixing temperatures, the Resilient modulus increases with increasing HDP content up to 4% HDP.

The 30 min. mixing time pronounces the differences between mixing temperatures. Resilient Modulus value for 165°C mixing temperatures are even higher, where those corresponding to 145 and 155°C mixing has dropped significantly.

As a result, prolonged mixing times and higher mixing temperatures give rise to higher Resilient Modulus. The higher the mixing temperature and the longer the mixing time, the higher will be the the Resilient Modulus. The graphs indicated that 4 % HDP content gives the highest Resilient Modulus.

CHAPTER 6

MATHEMATICAL MODEL FOR RESILIENT MODULUS OF HDP MODIFIED ASPHALT CONCRETE

6.1 INTRODUCTION

The object of model fitting is to obtain the simplest model that adequately fits the data, so that it can be useful for prediction purposes. The investigator may be considering several possible independent variables that could be included in the model; however, it may be time-consuming or expensive to obtain a general model which includes all the variables as they may increase the complexity of the standard errors of the estimates or add negligible accuracy.

6.2 REGRESSION ANALYSIS

When dealing with two or more variables, most often the functional relation between the variables is of interest. However, if one or both variables (in a two-variable case) are random, there will be no unique relationship between the values of the two variables- given a value of one variable (the controlled variable) there is a range of possible values of the other- and thus a probabilistic description is required. If the probabilistic relationship between the variables is described in terms of the mean and variance of one random variable as a function of the value of the other variable. When the analysis is limited to linear mean-value functions, it is called *linear regression*.

The value of an engineering variable may depend on several factors. In such cases, the mean and variance of the dependent variable will be a function of the values of

several variables. When the mean-value function is assumed to be linear, the resulting analysis is known as *multiple linear regression*.

Relationships between engineering variables are not always linear, or may not always be adequately described by linear models. Experimental data for such variables may show a nonlinear trend between the observed values of the variables. Although a linear relation may be used to describe the general trend between each pair of variables, predictions based on such linear relationships may overestimate (in certain ranges of the variables) or underestimate (in other ranges of the variables) the expected result. In such cases, a linear relationship between the variables would be more appropriate. The determination of such nonlinear relationships on the basis of observational data involves *nonlinear regression analysis*.

Nonlinear regression is usually based on an assumed nonlinear (mean value) function with certain undetermined coefficients that would be evaluated from the experimental data. The simplest type of nonlinear function for the regression of Y on X is

$$E(Y|x) = \alpha + \beta g(x) \quad (6.1)$$

where $g(x)$ is a predetermined nonlinear function of x . Nonlinear regression analysis is usually based on the assumption of a constant variance $\text{Var.}(Y | x)$, or a variance that is a function of $g(x)$ [2].

By defining a new variable $x' = g(x)$, Equation 6.1 becomes

$$E = (Y|x') = \alpha + \beta x' \quad (6.2)$$

The variables used in this study are as follows ;

$$\varepsilon_r = f(X_1, X_2, X_3, X_4) \quad (6.3)$$

Dependent variable :

ϵ_r : Total Recoverable Strain

Independent Variables :

X_1 : Polyethylene Content (0 – 2 – 4 – 6 - 8 %)

X_2 : Mixing Temperature (145°C - 155°C - 165°C)

X_3 : Mixing Time (5 min – 15 min - 30min)

X_4 : Rise Time (30 ms – 60 ms - 100 ms)

Models have been established with the total recoverable strain as the dependent variable because it was measured during the indirect tensile test. After the total recoverable strain during the test has been predicted by means of the model, the resilient modulus of the specimen can be determined from Equation 6.5. Average specimen height, and the diameter of all specimen was assumed 63.5 mm and 101,6 mm respectively.

$$M_R = \frac{P(\mu + 0.27)}{HD\epsilon_r 10^{-6}} \quad (6.4)$$

Four models were used for each test temperatures which are 5°C, 25°C, 40°C and 60°C.

6.3 THE MODEL FOR RESILIENT MODULUS (THE TESTS WERE PERFORMED AT 5°C)

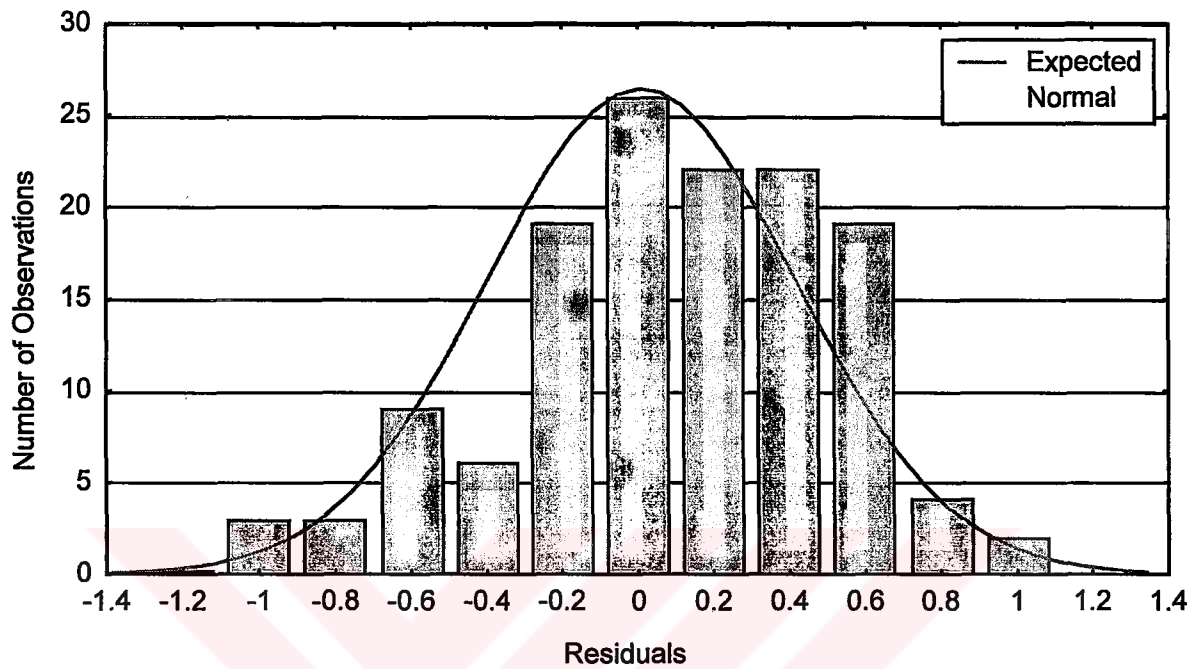


Figure 6.1 Frequency Distribution of Residuals of model established for specimens tested at 5°C

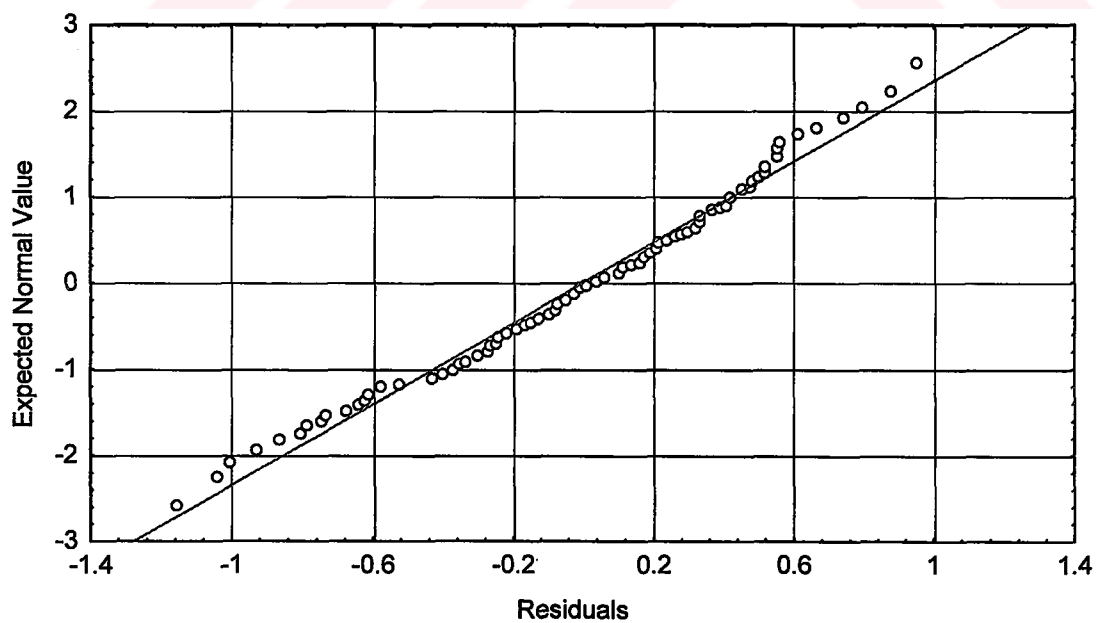


Figure 6.2 Normal Probability Plot of Residuals of model established for specimens tested at 5 °C

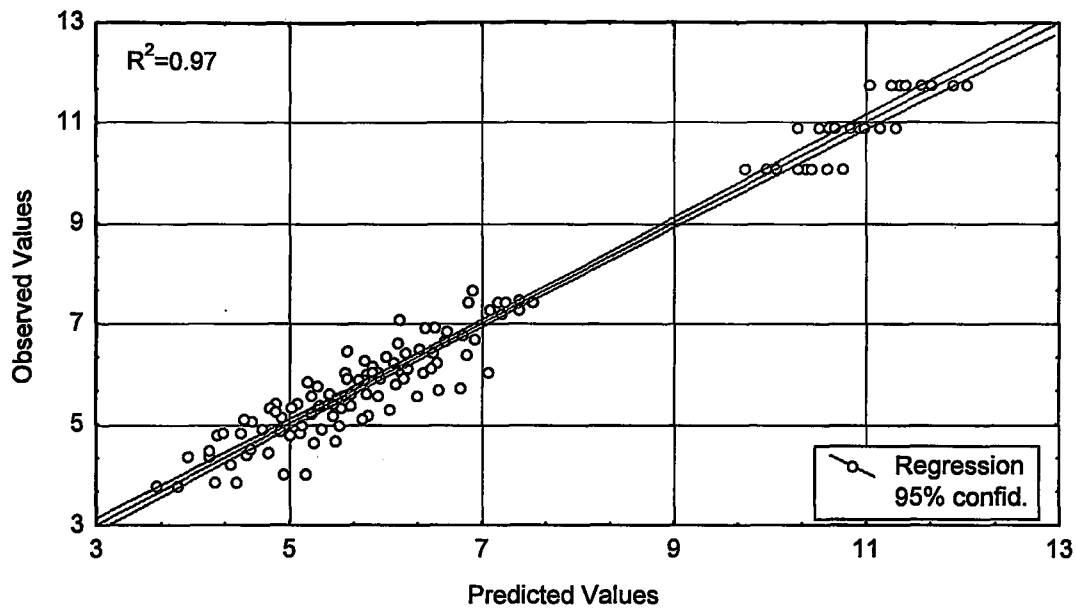


Figure 6.3 Observed and Predicted Values of model established for specimens tested at 5 °C

$$\epsilon_r = -0.062X_1^3 + 0.983X_1^2 - 4.475X_1 - 0.032X_2 - 0.015X_3 + 0.019X_4 + 14.89 \quad (6.5)$$

$$M_r = 650 \cdot (0.27 + 0.35) \cdot 10^{-6} / (101.6 \cdot 63.5 \cdot \epsilon_r) \quad (6.6)$$

$$M_r = 62481 / \epsilon_r \quad (6.7)$$

Table 6.1 Correlation Matrix of the Model Established for Specimens Tested at 5°C

	HDP Content	Mixing Temperature	Mixing Time	Rise Time	Total Recoverable Strain
HDP Content	1				
Mixing Temperature	-0,02566	1			
Mixing Time	-1,8E-18	0,00294389	1		
Rise Time	-2,6E-18	-0,02320546	6E-17	1	
Total Recoverable Strain	-0,51032	-0,116453002	-0,06739	0,234228	1

Table 6.2 Regression Statistics for 5°C Model

Multiple R	0.98334789
R Square	0.96697307
Adjusted R Square	0.96542493
Standard Error	0.4278312
Observations	135

Table 6.3 ANOVA Table for 5°C Model

	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	6	685.963514	114.3273	624.6041	3.23802E-92
Residual	128	23.42906079	0.18304		
Total	134	709.3925748			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>t Value</i>	<i>Comparison</i>	<i>P-value</i>
Constant	14.8850149	0.713448233	20.86348	1.65	20,86 > 1,65	5.22E-43
X_1^3	-0.0618083	0.002712409	-22.7872	1.65	-22,79 > 1,65	7.03E-47
X_1^2	0.98335683	0.033009244	29.79035	1.65	29,79 > 1,65	2.05E-59
X_1	-4.4754158	0.103978247	-43.0418	1.65	-43,04 > 1,65	5.35E-78
X_2	-0.03185526	0.004514637	-7.056	1.65	-7,06 > 1,65	9.63E-11
X_3	-0.01496174	0.003583991	-4.1746	1.65	-4,17 > 1,65	5.48E-05
X_4	0.01851447	0.001284482	14.41396	1.65	14,41 > 1,65	1.4E-28

When establishing the mathematical model, the correlation matrix (Figure 6.1) must first be calculated between the dependent and the probable independent variables. Since the correlations among HDP content, mixing time and rise time are weak, it is reasonable to choose all the three as independent variables and the total recoverable strain as the dependent variables and the total recoverable strain as the dependent variable. With 85% contribution, rise time is the most effective parameter on the strain recovered. Table 6.3 tabulates the regression coefficients. The values are all in the good correlation range. In Table 6.3, since all t-statistical values are greater than t-values, the calculated coefficients are all reasonable.

In order to determine whether or not any systematic errors are associated with the experiments, the frequency distribution of the residuals is plotted and compared with normal distribution. Figure 6.1 shows the both on the same graph. Since frequency distribution of the residuals conforms to normal distribution, no systematic error could possibly be associated. Figure 6.2 demonstrates the same result in a different plot. Good correlation is displayed between expected normal value and residual as well as between observed and predicted values.(Figure 6.3)

6.4 THE MODEL FOR THE RESILIENT MODULUS (THE TESTS WERE PERFORMED AT 25°C)

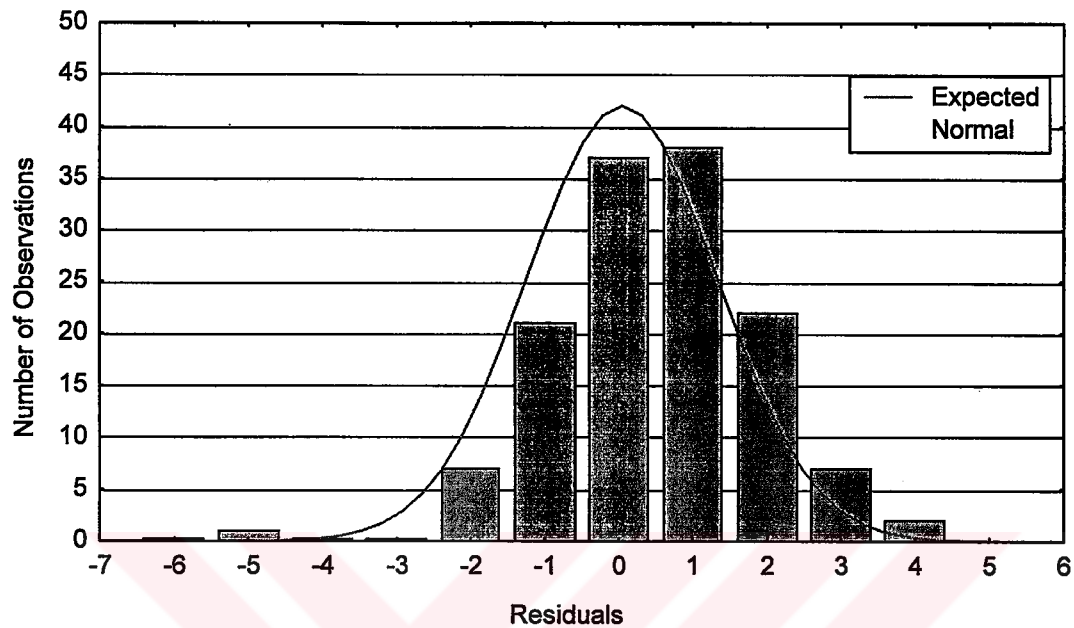


Figure 6.4 Frequency Distribution of Residuals of model established for specimens tested at 25 °C

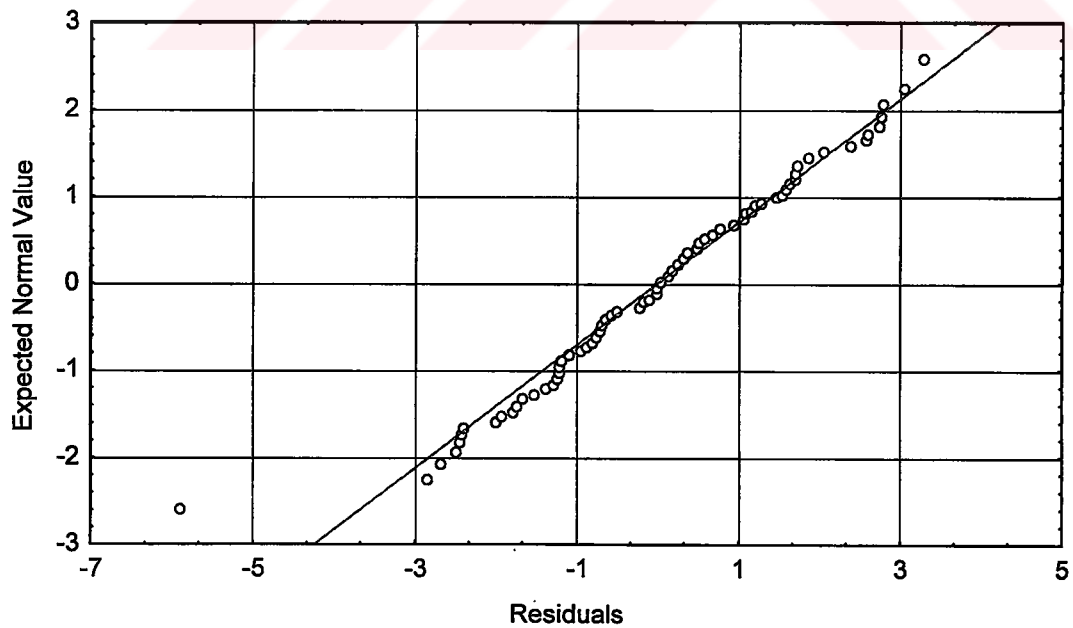


Figure 6.5 Normal Probability Plot of Residuals of model established for specimens tested at 25 °C

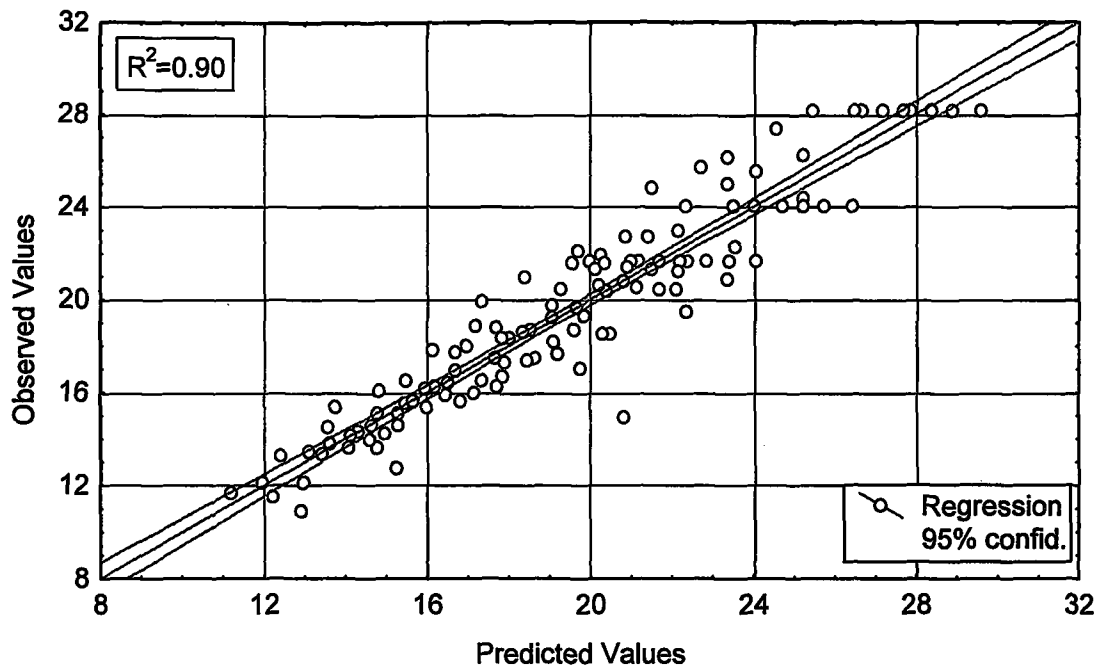


Figure 6.6 Observed and Predicted Values of model established for specimens tested at 25 °C

$$\epsilon_r = -0.084X_1^3 + 1.42X_1^2 - 6.52X_1 - 0.12X_2 - 0.068X_3 + 0.079X_4 + 39.46 \quad (6.8)$$

Table 6.4 Correlation Matrix of the Model Established for Specimens Tested at 25°C

	HDP Content	Mixing Temperature	Mixing Time	Rise Time	Total Recoverable Strain
HDP Content	1				
Mixing Temperature	-0,03855	1			
Mixing Time	-1,8E-18	0,061903287	1		
Rise Time	-2,6E-18	-0,06970827	6E-17	1	
Total Recoverable Strain	-0,21485	-0,26147866	-0,17642	0,53903	1

Table 6.5 Regression Statistics for 25°C Model

Adjusted R Square	0.893815397
Standard Error	1.408741202
Observations	135

Table 6.6 ANOVA Table for 25°C Model

	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	6	2250.388832	375.0648	188.9922	4.31231E-61
Residual	128	254.0226271	1.984552		
Total	134	2504.411459			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>t Value</i>	<i>Comparison</i>	<i>P-value</i>
Constant	39.4572491	2.363240556	16.69625	1.65	16,70 > 1,65	6.19E-34
X_1^3	-0.08362649	0.008931293	-9.36331	1.65	-9,36 > 1,65	3.44E-16
X_1^2	1.416461139	0.108693219	13.03173	1.65	13,03 > 1,65	3.12E-25
X_1	-6.52079775	0.342369866	-19.0461	1.65	-19,05 > 1,65	3.62E-39
X_2	-0.12000632	0.014949879	-8.02724	1.65	-8,03 > 1,65	5.57E-13
X_3	-0.06806402	0.011823963	-5.75645	1.65	-5,76 > 1,65	6.02E-08
X_4	0.078587863	0.004238707	18.54053	1.65	18,54 > 1,65	4.56E-38

6.5 THE MODEL FOR THE RESILIENT MODULUS (THE TESTS WERE PERFORMED AT 40°C)

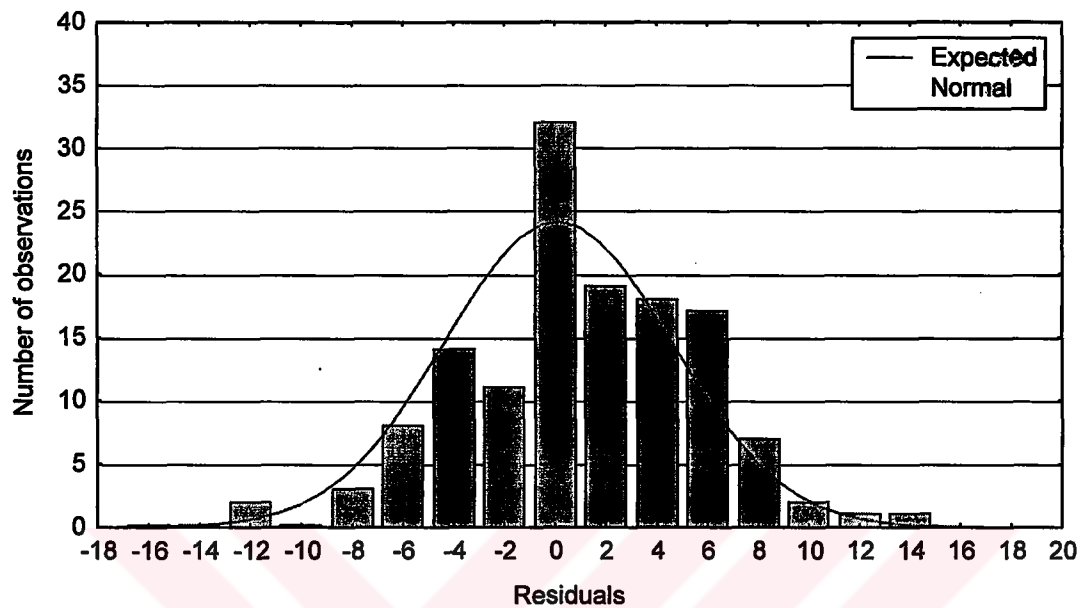


Figure 6.7 Frequency Distribution of Residuals of model established for specimens tested at 40°C

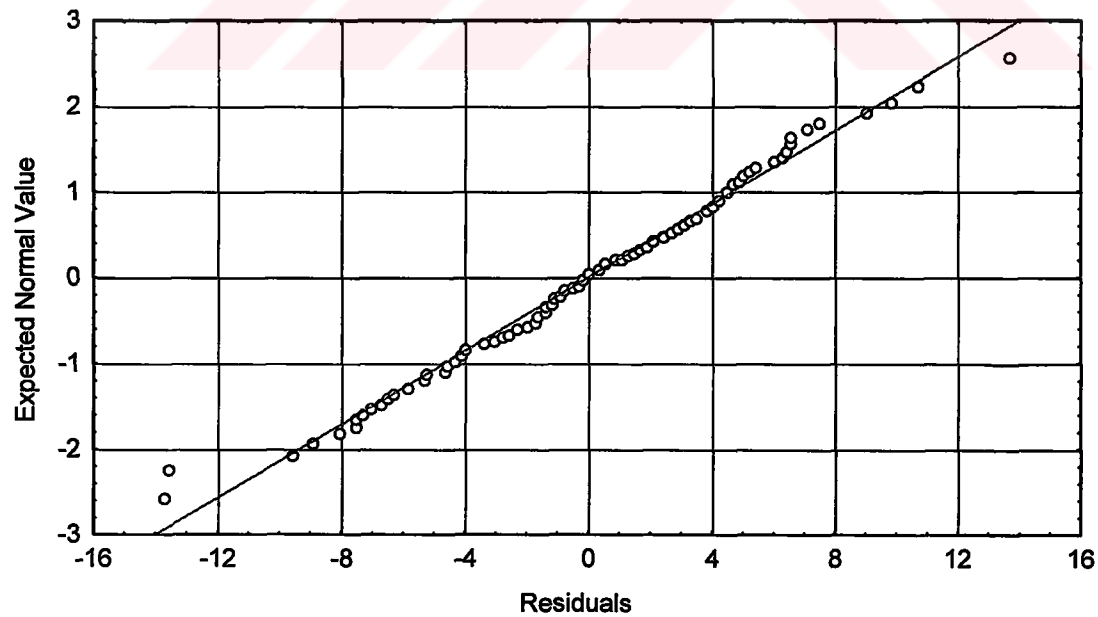


Figure 6.8 Normal Probability Plot of Residuals of model established for specimens tested at 40 °C

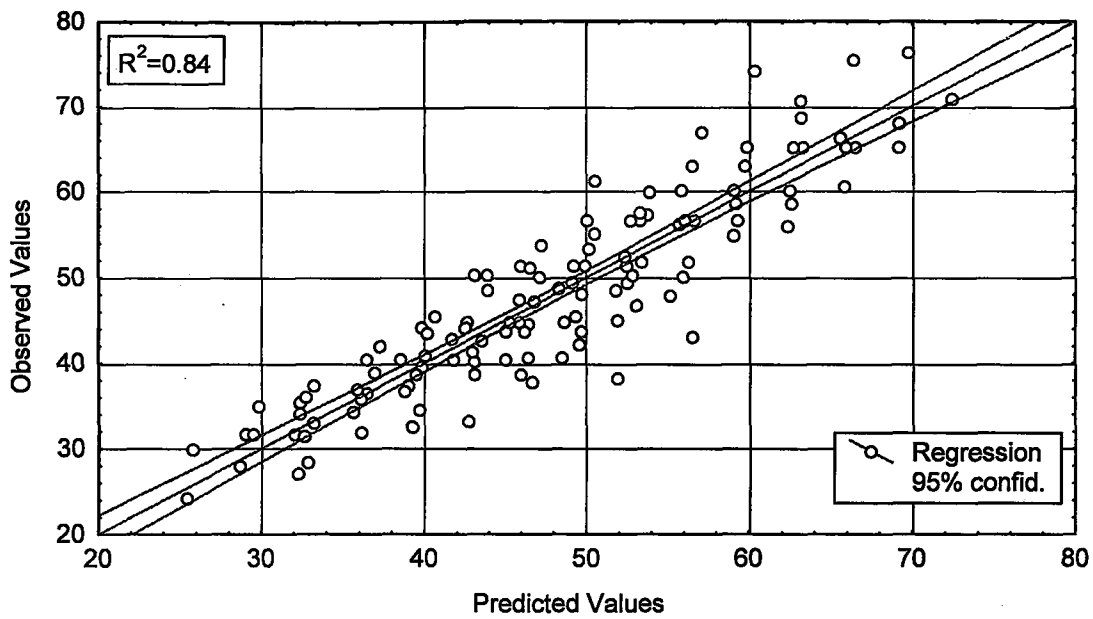


Fig 6.9 Variation of Observed Values with Predicted Values for specimens tested at 40°C

$$\varepsilon_e = -0.105X_1^3 + 2.177X_1^2 - 10.30X_1 - 0.329X_3 + 0.247X_4 + 93.64 \quad (6.9)$$

Table 6.7 Correlation Matrix of the Model Established for Specimens Tested at 40°C

	HDP Content	Mixing Temperature	Mixing Time	Rise Time	Total Recoverable Strain
HDP Content	1				
Mixing Temperature	0.00638	1			
Mixing Time	0.005915	5.0194E-18	1		
Rise Time	0.006055	-3.59689E-18	6E-17	1	
Total Recoverable Strain	0.153839	-0.246759879	-0.25624	0.614713	1

Table 6.8 Regression Statistics for 40°C Model

Multiple R	0,91526349
R Square	0,83770726
Adjusted R Square	0,83009979
Standard Error	4,70253521
Observations	135

Table 6.9 ANOVA Table for 40°C Model

	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	6	14610,57377	2435,096	110,1164	4,35855E-48
Residual	128	2830,571182	22,11384		
Total	134	17441,14495			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>t Value</i>	<i>Comparison</i>	<i>P-value</i>
Constant	93,6409671	7,797246628	12,00949	1,65	12,01 > 1,65	1,02E-22
X_1^3	-0,1048544	0,030000571	-3,49508	1,65	-3,50 > 1,65	0,000652
X_1^2	2,17669621	0,365092859	5,962034	1,65	5,96 > 1,65	2,27E-08
X_1	-10,302131	1,145741843	-8,99167	1,65	-8,99 > 1,65	2,76E-15
X_2	-0,3293597	0,049585743	-6,64222	1,65	-6,64 > 1,65	7,98E-10
X_3	-0,2730521	0,039404894	-6,9294	1,65	-6,93 > 1,65	1,85E-10
X_4	0,24749259	0,014118941	17,52912	1,65	17,53 > 1,65	7,99E-36

6.6 THE MODEL FOR THE RESILIENT MODULUS (THE TESTS WERE PERFORMED AT 60°C)

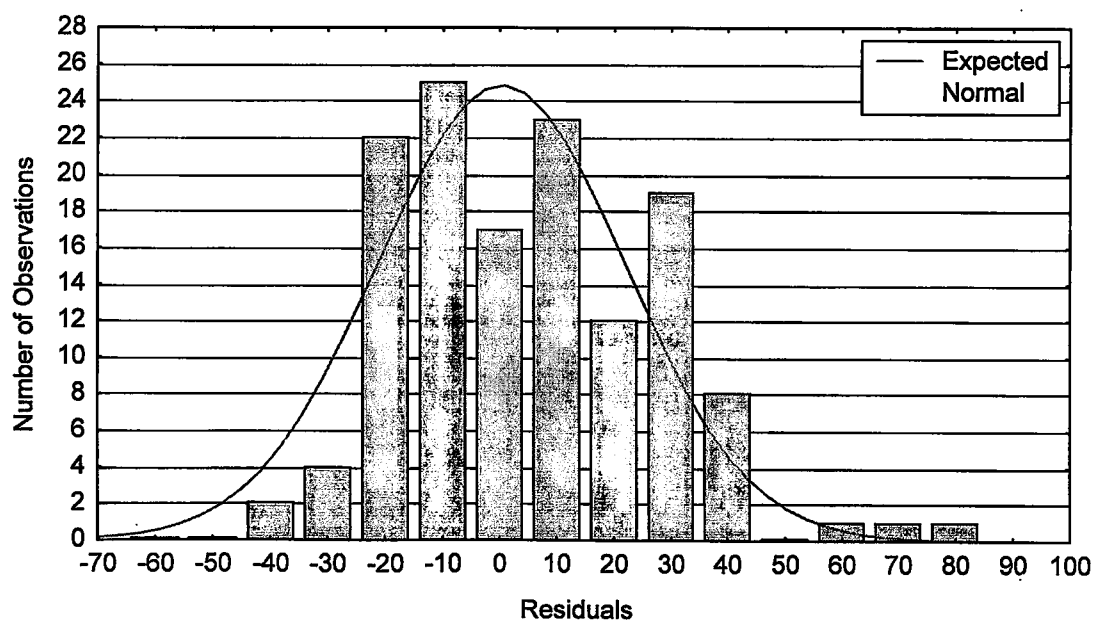


Figure 6.10 Frequency Distribution of Residuals of model established for specimens tested at 60 °C

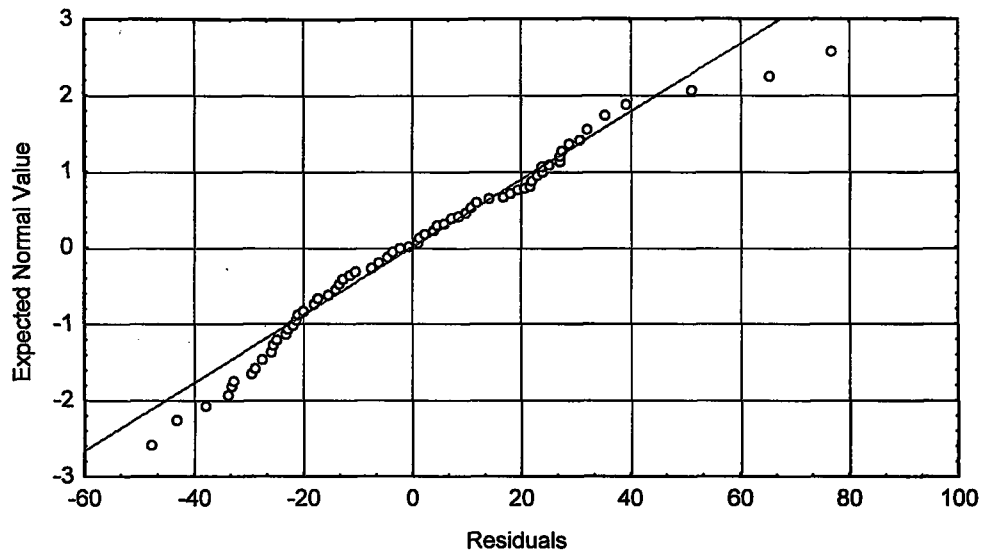


Figure 6.11 Normal Probability Plot of Residuals of model established for specimens tested at 60 °C

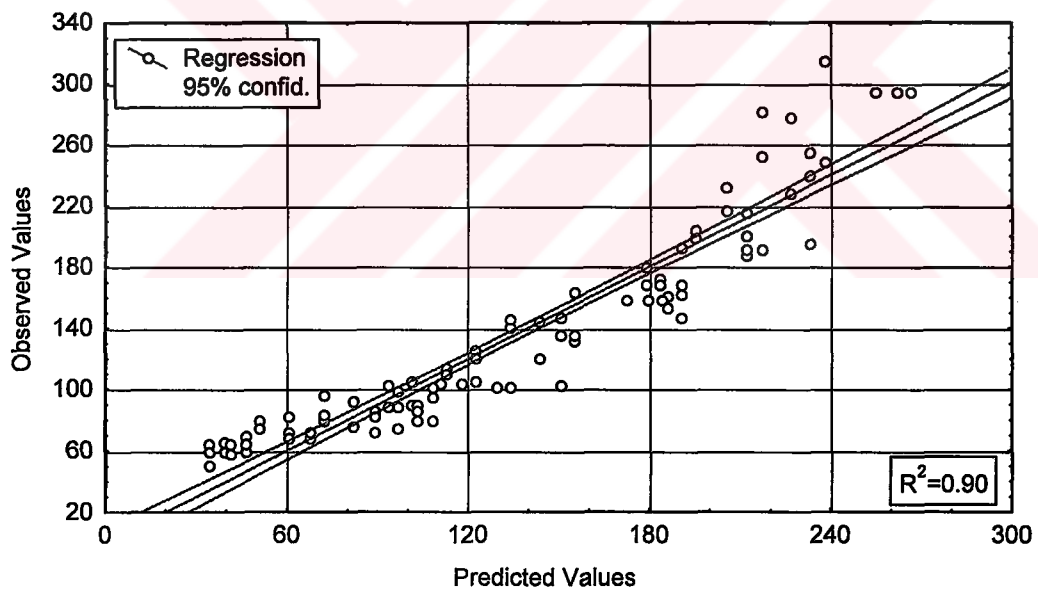


Figure 6.12 Observed and Predicted Values of model established for specimens tested at 60 °C

$$\varepsilon_r = -0.748X_1^3 + 12.839X_1^2 - 58.459X_1 - 0.467X_3 + 2.064X_4 + 62.71 \quad (6.10)$$

Table 6.10 Correlation Matrix of the Model Established for Specimens Tested at 60°C

	<i>HDP Content</i>	<i>Mixing Time</i>	<i>Rise Time</i>	<i>Total Recoverable Strain</i>
<i>HDP Content</i>	1			
<i>Mixing Time</i>	-1.9E-18	1		
<i>Rise Time</i>	-2.6E-18	-0.07148	1	
<i>Total Recoverable Strain</i>	-0.0731	-0.12754	0.855236	1

Table 6.11 Regression Istatistics for 60°C Model

Multiple R	0,94913822
R Square	0,90086337
Adjusted R Square	0,89702086
Standard Error	22,416001
Observations	135

Table 6.12 ANOVA Table for 60°C Model

	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	5	589020,9725	117804,2	234,4469	6,2142E-63
Residual	129	64819,54627	502,4771		
Total	134	653840,5188			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>t Value</i>	<i>Comparison</i>	<i>P-value</i>
Constant	62,7138221	6,9528871	9,019825	1,65	9,02 > 1,65	2,23E-15
X_1^3	-0,7475694	0,142103581	-5,26074	1,65	-5,26 > 1,65	5,8E-07
X_1^2	12,8388029	1,729432027	7,423711	1,65	7,42 > 1,65	1,37E-11
X_1	-58,458757	5,447804083	-10,7307	1,65	-10,73 > 1,65	1,36E-19
X_3	-0,4674199	0,19462615	-2,40163	1,65	-2,40 > 1,65	0,017748
X_4	2,06409936	0,067454212	30,60001	1,65	-30,60 > 1,65	5,41E-61

CHAPTER 7

CONCLUSIONS

Of the principal deteriorations encountered most in the flexible road pavements, the plastic deformations constitute a major problem in regard both to the traffic safety and cost of repair. To remedy these adverse effects, it is essential that both the mix design proportions be revised and the quality of the ingredients of the mix (the aggregates and the bituminous binder) be increased. Although it is possible to use aggregates with lower wearing ratios, their availability is restricted by limited geologic formations to several rock types, eg. basalt and granite. This restriction has drawn the attention of the researchers to the second element of the asphalt mix; the bituminous binder and hence the idea of modified asphalt was born.

In this study, an asphalt cement having a penetration value of 60-70 has been modified by a high density polyethylene (HDP) in proportions of 2-4-6-8 %. The specimens were prepared at 145-155 and 165°C mixing temperatures for 5-15-30 minutes mixing times. The rheologic properties of this mix have been investigated and Marshall tests have been carried out with 30-60 and 100 ms rise time at 5-25-40 and 60°C test temperatures. The following results have been obtained.

For a given mixing time and temperature, viscosity and softening point increases with increasing HDP content, whereas both penetration and ductility decreases. For a specific HDP content and mixing time, the higher the mixing temperature, the higher are the penetration and ductility and the lower are the viscosity and softening point. For a given HDP content and mixing temperature, longer mixing times result in higher penetration and ductility, yet giving rise to lower viscosity and softening point. It has been observed that when mixing time is short and the mixing temperature is low, the polyethylene can not be mixed in homogeneously but rather it covers the

outer faces of the specimen causing penetration to decrease. A similar problem has been observed in the ductility tests, that is for short mixing time and low mixing temperatures HDP particles, sticking to each other lump at arbitrary points, hence the specimen ruptures at these locations.

Marshall stability increases parabolically up to 4% HDP and decreases there on. Still the stability values at 6-8% HDP content are higher than those of control specimens. It has been observed that for a given HDP content and mixing temperature while void ratio and the percent voids filled with binder do not change, The Marshall stability increases with increasing mixing time. The same has been observed when HDP content and mixing time were kept constant and mixing temperature was varied. In other words, the effects of mixing time and mixing temperature on Marshall values are similar. The highest stability value (2400 kg) was obtained for 4% HDP, 165°C mixing temperature and 30 minutes mixing time. Thus, for maximum stability higher mixing temperatures and longer mixing times should be selected. However, since all stability values have come out to be higher than the specification lower limit (900 kg), in the selection of these parameters, economy should also be considered. In other words, in the decision, for various HDP contents Marshall stability values and the corresponding layer coefficients, layer thickness and mixing effort should be taken into consideration.

Marshall rigidity based on Marshall stability and Marshall flow values increases up to 4% HDP content and starts decreasing from that point. Marshall rigidity increases both with mixing time and temperature when the HDP content and the mixing temperature (or mixing time) are kept constant.

Void ratio falls within the limits of the specification for 2-4% HDP, but drastically increases at 6-8% HDP contents. At 6 and 8 % HDP contents owing to high binder viscosity proper mixing of binder and aggregate could not possibly be obtained and some aggregate particles were left uncovered by binder. The fact that the Marshall stability values dropped for HDP contents higher than 4% can be attributed to this unsuccessful mixing.

The resilient modulus follows a similar trend. That is, as in Marshall stability it reaches the maximum value around 4% HDP content. Higher HDP contents give lower resilient modulus. The modulus increases with increasing mixing temperatures for a given HDP content and mixing time. The values of Resilient modulus significantly lower for 145°C mixing but the values for 155°C and 165°C mixing temperatures were close to each other.

Similarly, for a given HDP content and mixing temperature, resilient modulus came out to be higher when the mixing time increased. It has been observed that 5 min. mixing time is unacceptable. 15 min. and 30 min. mixing has resulted in close values of resilient modulus, the value for 30 min. mixing being still higher.

For any given value of HDP content, mixing temperature, mixing time and rise time, the higher the test temperature, the lower were the resilient modulus. The highest resilient modulus obtained was 17000 MPa, at 5°C test temperature.

Under any test condition (test temperature, rise time) and for all modified bitumen preparations (polyethylene content, mixing time and temperature) resilient modulus reaches its maximum value at 4% polyethylene content.

When compared with unmodified control specimens, HDP modified specimens have shown relatively small deformations at 40°C and 60°C test temperatures, indicating that the modification improves the resistance of the asphalt concrete to loading at high temperatures. This result reveals the importance of the modification in hot climate regions where permanent deformations due to softening at high temperatures are the principal deteriorations.

Researchers have demonstrated that specimens with higher resilient modulus give longer fatigue life. Though no fatigue test has been carried out in this study on the specimens with modified asphalt, with this evidence at hand one can plausibly infer that HDP modified asphalt concrete must display a higher fatigue resistance.

Mathematical models describing the relationship between the resilient modulus and modified bitumen preparation and test conditions has been established for each test temperature separately, together with a general model inscribing all test temperatures (5-25-40 and 60 °C).

As a result, one can estimate that asphalt mixes prepared by bituminous binders modified by proper amount of HDP under suitable mixing time and temperature shall improve the performance of the pavement highly by mitigating permanent deformations observed in road pavements.

In future studies, it will be useful to use various penetration levels and attention should be focused on fatigue and creep tests.



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APPENDIX A

Table A.1 The results of total recoverable strain measurements (mm/mm) 10^{-6}
(Mixing Time : 5 minute and Test Temperature : 5°C)

	Mixing Time, 5 minute			Mixing Time , 5 min			Mixing Time , 5 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	10,07	10,90	11,77	10,07	10,90	11,77	10,07	10,90	11,77
2	5,49	5,62	6,23	5,16	5,33	6,42	4,52	5,06	5,90
4	5,05	5,84	6,03	4,82	5,27	5,93	4,31	5,10	5,78
6	5,90	6,41	7,42	5,38	5,93	6,68	5,38	6,02	6,66
8	6,15	6,77	7,45	5,55	6,13	7,20	6,47	7,10	7,68

Table A.2 The results of total recoverable strain measurements (mm/mm) 10^{-6}
(Mixing Time : 5 minute and Test Temperature : 25°C)

	Mixing Time , 5 min			Mixing Time , 5 min			Mixing Time , 5 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	21,67	24,01	28,19	21,67	24,01	28,19	21,67	24,01	28,19
2	17,75	20,98	24,80	16,02	18,76	21,59	13,69	15,21	17,90
4	15,11	17,44	20,83	13,58	15,86	18,65	10,89	12,76	14,89
6	18,46	21,97	26,13	17,74	19,76	22,95	16,54	18,31	20,92
8	17,06	20,43	24,40	18,71	21,42	25,50	19,90	22,07	26,21

Table A.3 The results of total recoverable strain measurements (mm/mm) 10^{-6}
(Mixing Time : 5 minute and Test Temperature : 40°C)

	Mixing Time , 5 min			Mixing Time , 5 min			Mixing Time , 5 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	44,88	56,56	65,16	44,80	56,56	65,16	44,80	56,56	65,16
2	38,20	51,09	56,62	36,95	42,52	51,24	31,46	40,73	51,23
4	36,54	43,69	52,21	34,00	41,27	50,27	27,00	34,37	42,08
6	47,35	56,78	68,57	44,02	53,43	64,80	32,55	37,72	43,00
8	47,82	58,55	70,82	48,47	58,56	67,99	40,53	50,10	60,60

Table A.4 The results of total recoverable strain measurements (mm/mm) 10^{-6}
(Mixing Time : 5 minute and Test Temperature : 60°C)

	Mixing Time , 5 min			Mixing Time , 5 min			Mixing Time , 5 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	104,29	158,19	294,15	104,29	158,19	294,15	104,29	158,19	294,15
2	79,31	113,67	204,27	77,73	110,30	201,01	74,37	112,25	199,14
4	67,54	97,61	189,71	64,50	103,40	191,28	64,06	95,16	170,61
6	80,14	101,15	191,05	84,04	140,67	281,99	95,65	145,67	252,11
8	88,88	132,09	248,07	89,83	135,90	248,86	103,20	164,00	314,95

Table A.5 The results of total recoverable strain measurements (mm/mm) 10^{-6}
(Mixing Time : 15 minute and Test Temperature : 5°C)

	Mixing Time , 15 min			Mixing Time , 15 min			Mixing Time , 15 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	10,07	10,90	11,77	10,07	10,90	11,77	10,07	10,90	11,77
2	5,40	5,61	6,04	4,52	4,92	5,27	3,87	4,78	5,13
4	4,88	5,33	5,87	4,47	4,90	5,40	3,77	4,20	4,98
6	6,00	6,52	7,27	4,67	5,28	5,73	4,00	5,88	6,87
8	6,22	6,85	7,48	5,12	5,58	6,05	5,17	6,33	7,30

Table A.6 The results of total recoverable strain measurements (mm/mm) 10^{-6}
(Mixing Time : 15 minute and Test Temperature : 25°C)

	Mixing Time , 15 min			Mixing Time , 15 min			Mixing Time , 15 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	21,67	24,01	28,19	21,67	24,01	28,19	21,67	24,01	28,19
2	15,33	18,76	22,71	14,16	16,41	19,63	12,12	14,54	17,34
4	14,55	18,02	21,31	13,31	16,37	19,28	11,51	13,92	16,22
6	18,82	21,59	25,73	15,33	18,60	21,31	13,57	15,94	18,51
8	19,20	22,74	27,34	16,65	20,63	24,99	15,55	18,29	21,26

Table A.7 The results of total recoverable strain measurements (mm/mm) 10^{-6}
(Mixing Time : 15 minute and Test Temperature : 40°C)

	Mixing Time , 15 min			Mixing Time , 15 min			Mixing Time , 15 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	44,80	56,56	65,16	44,80	56,56	65,16	44,80	56,56	65,16
2	40,33	48,51	57,30	37,27	45,47	54,97	34,91	42,01	49,90
4	35,85	42,62	51,69	35,88	43,54	53,28	31,61	38,84	47,18
6	50,16	61,18	74,10	44,07	53,65	66,94	40,72	50,23	59,84
8	52,36	62,83	76,29	51,93	62,96	75,44	47,40	57,48	70,62

Table A.8 The results of total recoverable strain measurements (mm/mm) 10^{-6}
(Mixing Time : 15 minute and Test Temperature : 60°C)

	Mixing Time , 15 min			Mixing Time , 15 min			Mixing Time , 15 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	104,29	158,19	294,15	104,29	158,19	294,15	104,29	158,19	294,15
2	69,78	100,74	192,91	67,41	95,04	161,78	59,91	80,27	147,23
4	64,27	89,61	160,83	63,93	85,78	164,02	58,24	80,14	151,99
6	68,85	101,00	187,05	71,38	99,83	191,98	72,67	104,22	216,21
8	72,22	102,97	195,40	85,72	146,45	255,13	82,84	135,25	252,62

Table A.9 The results of total recoverable strain measurements (mm/mm) 10^{-6}
(Mixing Time : 30 minute and Test Temperature : 5°C)

	Mixing Time , 30 min			Mixing Time , 30 min			Mixing Time , 30 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	10,07	10,90	11,77	10,07	10,90	11,77	10,07	10,90	11,77
2	5,41	5,62	6,03	4,40	4,83	5,22	3,85	4,45	5,00
4	4,80	5,32	5,58	4,38	4,82	5,22	3,78	4,37	4,88
6	6,05	6,60	7,42	4,65	5,18	5,68	4,00	5,53	6,13
8	6,15	6,93	7,42	5,35	5,82	6,40	5,55	6,25	6,93

Table A.10 The results of total recoverable strain measurements (mm/mm) 10^{-6}
(Mixing Time : 30 minute and Test Temperature : 25°C)

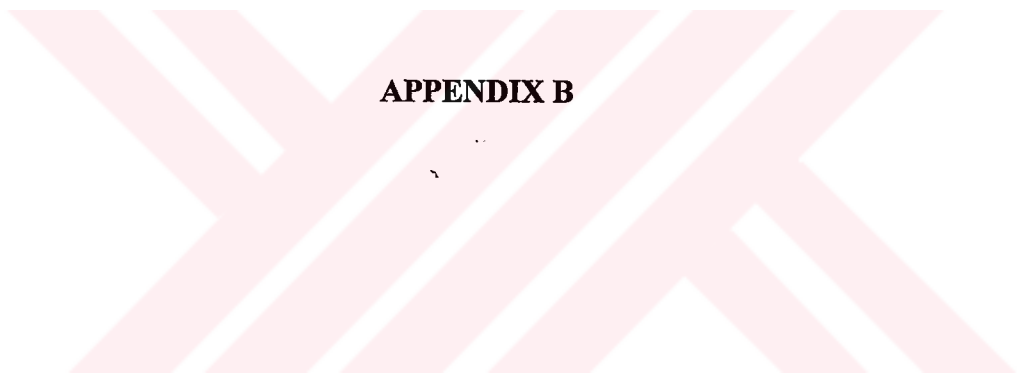
	Mixing Time , 30 min			Mixing Time , 30 min			Mixing Time , 30 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	21,67	24,01	28,19	21,67	24,01	28,19	21,67	24,01	28,19
2	14,33	16,94	19,31	13,47	15,56	17,44	12,08	14,54	16,68
4	13,77	16,18	18,18	13,22	15,06	17,31	11,69	14,48	15,47
6	16,21	18,72	20,41	14,25	16,51	18,55	15,35	17,82	20,41
8	18,38	20,31	22,24	15,59	17,67	19,48	15,63	18,13	20,50

Table A.11 The results of total recoverable strain measurements (mm/mm) 10^{-6}
(Mixing Time : 30 minute and Test Temperature : 40°C)

	Mixing Time , 30 min			Mixing Time , 30 min			Mixing Time , 30 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	40,44	51,40	60,00	40,44	51,40	60,00	40,44	51,40	60,00
2	34,08	39,48	48,04	31,51	36,48	40,60	29,82	33,02	38,52
4	31,70	38,55	45,37	27,94	31,86	38,51	24,20	28,27	33,16
6	37,38	44,52	51,78	34,33	40,23	46,73	35,28	39,51	43,57
8	48,65	56,24	66,15	43,64	49,40	55,85	42,79	49,24	54,91

Table A.12 The results of total recoverable strain measurements (mm/mm) 10^{-6}
(Mixing Time : 30 minute and Test Temperature : 60°C)

	Mixing Time , 30 min			Mixing Time , 30 min			Mixing Time , 30 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	104,29	158,19	294,15	104,29	158,19	294,15	104,29	158,19	294,15
2	66,07	105,44	172,56	62,74	90,35	168,28	59,61	86,82	168,45
4	65,00	98,49	179,77	59,29	88,71	168,32	50,88	75,16	152,96
6	82,06	125,49	232,26	71,73	120,72	216,96	67,78	105,08	200,53
8	91,86	144,95	277,55	75,71	120,93	228,22	77,55	122,68	239,81



APPENDIX B

Table B.1 The Results of Resilient Modulus Tests (MPa)
(Test Temperature: 5°C and Mixing Time: 5 minute)

	Mixing Time , 5 min			Mixing Time , 5 min			Mixing Time , 5 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	8864,00	6950,00	9431,00	8864,00	6950,00	9431,00	8864,00	6950,00	9431,00
2	12192,00	11820,00	10535,00	14401,00	12733,00	10913,00	14670,00	12817,00	11057,00
4	13688,00	11237,00	10673,00	15017,00	12542,00	11030,00	15226,00	12675,00	11788,00
6	11497,00	10445,00	8692,00	11681,00	10435,00	9444,00	12648,00	11303,00	9862,00
8	10197,00	9308,00	8402,00	10288,00	9325,00	8507,00	11408,00	10231,00	8711,00

Table B.2 The Results of Resilient Modulus Tests (MPa)
(Test Temperature: 25°C and Mixing Time: 5 minute)

	Mixing Time , 5 min			Mixing Time , 5 min			Mixing Time , 5 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	3419,00	2900,00	2423,00	3419,00	2900,00	2423,00	3419,00	2900,00	2423,00
2	4156,00	3489,00	2855,00	4272,00	3607,00	3158,00	4666,00	4183,00	3555,00
4	5032,00	4271,00	3399,00	5471,00	4518,00	3749,00	6056,00	5129,00	4384,00
6	3541,00	2980,00	2488,00	3894,00	3346,00	2839,00	4165,00	3716,00	3246,00
8	3786,00	3146,00	2647,00	3410,00	2986,00	2503,00	3828,00	3281,00	2686,00

Table B.3 The Results of Resilient Modulus Tests (MPa)
(Test Temperature: 40°C and Mixing Time: 5 minute)

	Mixing Time , 5 min			Mixing Time , 5 min			Mixing Time , 5 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	1424,00	1134,00	976,00	1424,00	1134,00	976,00	1424,00	1134,00	976,00
2	1634,00	1352,00	1141,00	1727,00	1470,00	1220,00	2183,00	1821,00	1414,00
4	1855,00	1553,00	1276,00	1986,00	1615,00	1301,00	2263,00	1840,00	1503,00
6	1508,00	1241,00	1018,00	1638,00	1313,00	1057,00	1997,00	1747,00	1520,00
8	1378,00	1125,00	936,00	1310,00	1083,00	925,00	1705,00	1366,00	1124,00

Table B.4 The Results of Resilient Modulus Tests (MPa)
(Test Temperature: 60°C and Mixing Time: 5 minute)

	Mixing Time , 5 min			Mixing Time , 5 min			Mixing Time , 5 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	619,00	408,00	219,00	619,00	408,00	219,00	619,00	408,00	219,00
2	942,00	640,00	335,00	1015,00	676,00	334,00	1080,00	699,00	338,00
4	979,00	683,00	353,00	993,00	616,00	378,00	1010,00	686,00	410,00
6	829,00	626,00	333,00	757,00	460,00	228,00	670,00	449,00	255,00
8	717,00	487,00	259,00	705,00	472,00	259,00	619,00	390,00	202,00

Table B.5 The Results of Resilient Modulus Tests (MPa)
(Test Temperature: 5°C and Mixing Time: 15 minute)

	Mixing Time , 15 min			Mixing Time , 15 min			Mixing Time , 15 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	8864,00	6951,00	6431,00	8864,00	6951,00	6431,00	8864,00	6951,00	6431,00
2	12372,00	12151,00	10573,00	14641,00	13492,00	12683,00	16933,00	13708,00	12779,00
4	13971,00	12357,00	11119,00	15684,00	14174,00	12668,00	18014,00	15861,00	13042,00
6	11192,00	10031,00	8953,00	14519,00	12580,00	11478,00	12835,00	10630,00	9074,00
8	10212,00	9209,00	8436,00	13876,00	12478,00	11407,00	12211,00	9837,00	8549,00

Table B.6 The Results of Resilient Modulus Tests (MPa)
(Test Temperature: 25°C and Mixing Time: 15 minute)

	Mixing Time , 15 min			Mixing Time , 15 min			Mixing Time , 15 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	3419,00	2900,00	2423,00	3419,00	2900,00	2423,00	3419,00	2900,00	2423,00
2	4211,00	3668,00	2930,00	4921,00	4198,00	3466,00	5821,00	4652,00	3876,00
4	5544,00	4617,00	3522,00	5921,00	5073,00	3971,00	6278,00	5200,00	4522,00
6	3455,00	2995,00	2504,00	4586,00	3550,00	3049,00	4718,00	4006,00	3436,00
8	3260,00	2754,00	2291,00	4661,00	3440,00	2705,00	4161,00	3531,00	3002,00

Table B.7 The Results of Resilient Modulus Tests (MPa)
(Test Temperature: 40°C and Mixing Time: 15 minute)

	Mixing Time , 15 min			Mixing Time , 15 min			Mixing Time , 15 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	1424,00	1134,00	976,00	1424,00	1134,00	976,00	1424,00	1134,00	976,00
2	1895,00	1397,00	1262,00	1820,00	1511,00	1349,00	2348,00	1828,00	1531,00
4	2036,00	1697,00	1406,00	2203,00	1738,00	1442,00	2376,00	1912,00	1538,00
6	1324,00	1093,00	900,00	1675,00	1341,00	1094,00	1583,00	1294,00	1094,00
8	1218,00	1004,00	828,00	1457,00	1202,00	996,00	1444,00	1192,00	963,00

Table B.8 The Results of Resilient Modulus Tests (MPa)
(Test Temperature: 60°C and Mixing Time: 15 minute)

	Mixing Time , 15 min			Mixing Time , 15 min			Mixing Time , 15 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	619,00	408,00	219,00	619,00	408,00	219,00	619,00	408,00	219,00
2	976,00	707,00	397,00	1125,00	750,00	400,00	1201,00	799,00	435,00
4	1016,00	740,00	406,00	1028,00	770,00	410,00	1158,00	860,00	452,00
6	929,00	637,00	345,00	931,00	673,00	341,00	890,00	626,00	310,00
8	918,00	624,00	327,00	741,00	432,00	262,00	760,00	468,00	253,00

Table B.9 The Results of Resilient Modulus Tests (MPa)
(Test Temperature: 5°C and Mixing Time: 30 minute)

	Mixing Time , 30 min			Mixing Time , 30 min			Mixing Time , 30 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	8864,00	6951,00	6431,00	8864,00	6951,00	6431,00	8864,00	6951,00	6431,00
2	13550,00	12342,00	10599,00	14993,00	13711,00	12716,00	17432,00	14653,00	13038,00
4	14742,00	12446,00	12295,00	16032,00	14301,00	13159,00	18693,00	16047,00	13053,00
6	11231,00	10103,00	8831,00	14236,00	12572,00	11503,00	13500,00	11467,00	10303,00
8	10380,00	9107,00	8509,00	12429,00	11274,00	10134,00	11467,00	10139,00	9182,00

Table B.10 The Results of Resilient Modulus Tests (MPa)
(Test Temperature: 25°C and Mixing Time: 30 minute)

	Mixing Time , 30 min			Mixing Time , 30 min			Mixing Time , 30 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	3419,00	2900,00	2423,00	3419,00	2900,00	2423,00	3419,00	2900,00	2423,00
2	4596,00	3866,00	3366,00	6073,00	5019,00	4220,00	6182,00	4746,00	4044,00
4	5926,00	4839,00	4078,00	6187,00	4822,00	4008,00	5524,00	4407,00	4085,00
6	4523,00	3871,00	3494,00	4902,00	4139,00	3606,00	4108,00	3505,00	3059,00
8	3746,00	3347,00	3031,00	4753,00	1430,00	3631,00	4173,00	3542,00	3117,00

Table B.11 The Results of Resilient Modulus Tests (MPa)
(Test Temperature: 40°C and Mixing Time: 30 minute)

	Mixing Time , 30 min			Mixing Time , 30 min			Mixing Time , 30 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	1687,00	1240,00	1116,00	1687,00	1240,00	1116,00	1687,00	1240,00	1116,00
2	1987,00	1663,00	1890,00	2119,00	1799,00	1596,00	2571,00	1951,00	1671,00
4	2179,00	1754,00	1479,00	2408,00	2093,00	1718,00	2643,00	2264,00	1924,00
6	1838,00	1530,00	1290,00	1868,00	1584,00	1359,00	1803,00	1612,00	1457,00
8	1414,00	1201,00	1008,00	1514,00	1321,00	1158,00	1497,00	1297,00	1156,00

Table B.12 The Results of Resilient Modulus Tests (MPa)
(Test Temperature: 60°C and Mixing Time: 30 minute)

	Mixing Time , 30 min			Mixing Time , 30 min			Mixing Time , 30 min		
	Mixing Temperature, 145°C			Mixing Temperature, 155°C			Mixing Temperature, 165°C		
HDP content	Rise Time (ms)			Rise Time (ms)			Rise Time (ms)		
(%)	30	60	100	30	60	100	30	60	100
0	619,00	408,00	219,00	619,00	408,00	219,00	619,00	408,00	219,00
2	1005,00	810,00	422,00	1227,00	855,00	453,00	1200,00	1010,00	471,00
4	1038,00	771,00	575,00	1095,00	795,00	612,00	1254,00	860,00	643,00
6	790,00	517,00	276,00	900,00	554,00	300,00	951,00	628,00	322,00
8	688,00	445,00	234,00	842,00	536,00	286,00	820,00	521,00	265,00

CURRICULUM VITAE

Sinan HINISLIOĞLU was born in Erzurum 1965. Then, he finished primary school at İsmet Paşa İlkokulu in Erzurum and secondary school at Akhisar Lisesi in Manisa. He started university education at Dokuz Eylül University in 1982. He finished university in 1988. Thereafter, he started graduate education at Dokuz Eylül University, Institute of Science and Technology, Civil Engineering Division, Transportation Program at the same year. After that, he started to work at Atatürk University, Civil Engineering Faculty, Transportation Division as a research assistant in 1989. Later, he finished his graduate education in 1991. Then, he started doctorate studies at the İ.T.Ü. Institute of Science and Technology, Civil Engineering Division, Transportation Program in 1992.