Evaluation the Physical Properties and Marshall Stability for Asphalt Modified with Waste Polypropylene and Nanosilica Powder

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Abstract. Recently, Nanotechnology was being widely accepted in many fields due to its unique properties in enhancing the characteristics of many different kinds of materials, including asphalt binder. On the other hand, the usage of polymer nanocomposites for the production of durable asphalt mixtures has steadily replaced the use of polymer-modified binders. This study investigates the influence of nanosilica particles (NS) on rheological properties and mixture performance of asphalt modified with 2% waste polypropylene polymer (WPP). In laboratory work, NS/WPP composite modified asphalt samples have been produced by adding three different percentages of NS particles (0.5, 1, and 2%) by weight of binder and 2% WPP to control asphalt (60-70) penetration grade using a mechanical mixer and a homogenizer shear mixer with shear rate 27000 rpm for 10 min at mixing temperature (165 ±5) ºC. The physical tests and Marshall stability were used to evaluate the NS/WPP composite modified asphalt binder properties and mixtures performance characteristics. This study found that 2% of NS particles decrease the temperature sensitivity of WPP modified asphalt by 13% due to improving the hardness of the NS/WPP composite modified binder. The results also showed that the Marshall stability values of NS/WPP composite modified asphalt mixtures improved by 34.2% and 9.71% at 2% NS compared with the control and WPP modified asphalt mixtures respectively. This suggests that the composite NS/WPP composite has a noticeable effect on the performance of the flexible pavement, thus increase paving's service life.

Keywords: Modified Asphalt, Nanocomposite Polymer Binder, Nanosilica, rheological properties, Thermoplastic Polymer.

1. Introduction
During the paving's service life, loads are applied to asphalt pavements in conjunction with the hard environmental conditions and the increasing environmental requirements of the usage of the highway network, contribute to the deterioration of the pavement and poor pavement performance, thus reducing its service life [1]. The service life of the pavement is one of the critical problems to still be discussed for economic growth and other purposes [2]. Therefore, the efficiency of the asphalt mixture should be enhanced by improving the existing asphalt materials used in asphalt mixtures [3]. Modification is the commonly used method for increasing the efficiency of asphalt pavements [4]. Polymers are mostly used to modify the asphalt as well as a special type of thermoplastics and thermosetting [5,6]. Although the
polymer-modified asphalt binder improves pavement resistance to thermal cracking and fatigue cracking and rutting resistance, it suffers from a major problem of incompatibility with asphalt and separation in two phases during storage [3]. This issue has motivated researchers to create an asphalt binder by testing a variety of alternatives.

Nowadays, Nanotechnology considers a hopeful and innovative technique in the materials industry, nanomaterial have been used extensively used in different fields around the world [7]. A nanomaterial is defined as a material having one or more dimensions within 1–100 nm. Due to its large surface area and small size, the nanomaterials have distinct characteristics compared to the usual material and show some novel properties and amazing features that make it possible to be used as an additive in the field of asphalt pavement [8,9]. Several varieties of nanomaterials are recurrently used in asphalt enhancement, like nano-clay, nano-silica, nano-titanium oxide, carbon nanotube, and nano-hydrated lime [10]. Since nanomaterials are more compatible with bitumen compared to polymers with bitumen, as well as to improve the properties of asphalt binders, the application of nanomaterials in combination with polymers is significant [11,12]. As a result, academics and industrial societies have increased interest in the development of polymer nanocomposites.

Polymer nanomixtures have been identified as the mixing of polymers into nanomaterials, for example, nano clay, nanosilica [13]. Researchers have concluded that nanosilica powder was used to reinforce polymers [14]. Alhamali, & Hassan, 2016 [13] was found that the rheological properties abrasion resistance improved when adding nanosilica with polymer modified binder.

Until now, most of the current research at nanomaterial asphalt modification concentrates exclusively on the implementation of virgin elastic composites like styrene-butadiene-styrene (SBS) copolymer, and evaloy (EV) [15]. Related studies in nanomaterials and nanocomposite polymer asphalt modification have found a rise in optimum content of 4–8 % by weight of asphalt, which is not promising because it increases the modification expenses [3,7,16]. Nevertheless, the high content of nanomaterials using to modify asphalt binders taking into account the expense of nanomaterials still needs to be studied because nanomaterials are still costly [2].

On the other hand, Iraq has seen an increase in the number of solid plastic waste generated from consumer products, including plastic packaging. Solid waste disposal remains one of the greatest environmental concerns in the world. Increased use of waste materials, such as polypropylene, in the building industry, has resulted in reduced handling and disposal of this waste. Accordingly, the newest project examines the use of low-cost polypropylene polymer which can be produced from everyday waste with the addition of nanosilica at a lower level by (0.5%–2%) by weight of asphalt with double increment.

The main objective of this study is to investigate the impact of combination waste polypropylene polymer (WPP) with nanosilica (NS) particles on the physical properties and mixture performance of non-modified, and polymer-modified asphalt (PMA). The present research will help to clarify the performance characteristics of nanosilica composite polymer modified asphalt (NS/PMA) mixtures in command to enhance the design of high-performance bitumen mixture.

2. Research plan

'Figure 1’ demonstrates the work plan of this research, which aims to evaluate the effects of the addition of waste polymer and nanosilica powder on the physical properties of 60/70 bitumen penetration grade, including penetration, softening point, and ductility. Marshall's stability and flow have also been studied.
3. Materials

3.1. Asphalt
The asphalt binder in this work has been obtained from AL-Daurah Refinery, with a penetration grade of (60-70). The physical properties of asphalt were implemented in the laboratory and listed in (table 1).

| Property                      | Standard | Value | (SCRB/ R9, 2003) specification |
|-------------------------------|----------|-------|-------------------------------|
| Penetration                   | ASTM D5  | 67    | 60-70                         |
| 100 gm, 25°C, 5 sec., (0.1mm) |          |       |                               |
| Ductility25°C, 5cm/min        | ASTM D113| +140  | >100                          |
| Softening Point °C            | ASTM D36 | 47    | ----                          |
| Specific gravity              | ASTM D70 | 1.03  | ----                          |
| Flash and fire point °C       | ASTM D92 | 298°C | > 232 °C                      |
| Rotational Viscosity          | ASTM D4402| @ 135 °C 430 | ---- |
|                               |          |       |                               |
| Pa.sec                        |          | @ 165 °C 128 | ---- |

3.2. Waste Polypropylene Polymer (WPP)
Polypropylene is a synthetic polymer obtained from everyday waste. It has the C3H6 chemical formula. The chemical and physical properties of polypropylene waste are shown in (table 2) according to the plastic manufacturer from which the waste was obtained. ‘Figure 2-a,b’ shows the waste polypropylene polymer (WPP) was used in this study.

| Property            | Unit    | Value  |
|---------------------|---------|--------|
| Density             | g/cm³   | 0.91-0.94 |
| Softening Point     | °C      | 140-150  |
| Melting Point, Tm   | °C      | 170     |
3.3. Nanosilica Powder (NS)
Nanosilica is a white color and hydrophobic powder, chemical designation SiO2. Synthetic amorphous silica was used in this study to modified the binder imported from AEROSIL Company in North American and shown in ‘figure 2-c’. The chemical and physical characteristics of nanosilica according to the manufacturer characteristics are listed in (table 3).

| Physical properties of Nano SiO2 Powder. |
|-----------------------------------------|
| Property | Result  |
|----------|---------|
| Physical form | Powder  |
| Color | white |
| size | 11-12 nm |
| Bulk Density g/cm³ | 0.1< |
| True Density g/cm³ | 2.4 |
| Specific surface area m²/g | 200 |
| Purity % | 99.8 |
| PH | 3.7-4.5 |

Figure 2. (a) Waste polypropylene polymer before the grinding process, (b) Waste polypropylene polymer after grinding process and sieving on sieve #50, (c) Nanosilica SiO2 powder.

3.4. Aggregate gradation
‘Table 4’ & ‘figure 3’ shows the aggregate gradation was chosen to meet the surface course gradation type IIIA, as needed by SCRB specification (SCRB, R/9 2003) for paving mixtures of aggregate nominal size (12.5 mm).

| Sieve Size | Sieve Opening, mm | Percentage passing by Weight of total Aggregate Specification Limits [S.C.R.B] | Mid-Point Gradation |
|------------|-------------------|---------------------------------------------------------------------------------|--------------------|
| 3/4"       | 19                | 100                                                                             | 100                |
| 1/2"       | 12.5              | 90 - 100                                                                        | 95                 |
| 3/8"       | 9.5               | 76 - 90                                                                         | 83                 |
| #4         | 4.75              | 44 - 74                                                                         | 59                 |
| #8         | 2.36              | 28 - 58                                                                         | 43                 |
| #50        | 0.3               | 5 - 21                                                                          | 13                 |
| #200       | 0.075             | 4 - 10                                                                          | 7                  |
3.5. Mixer Type
According to the study conducted by researcher Hussein, 2019 [17], and to ensure a homogeneous mixture, two laboratory mixers were used in mixing technique to prepare the nanosilica composite polymer modified asphalt: the classic mechanical mixer, and the homogeneous shear mixer. ‘Figure 4’ shows the mixers were used in this study.

3.5.1. Mechanical Mixer
An apparatus that has constant motor rotational speed estimated by 1370 rpm along the time of mixing. Mixing time-based on the operator’s opinion and the additive type. This mixer was used as the first step in the composite modified asphalt preparation process.

3.5.2. Homogenizer Shear Mixer
Due to the small size of the nanosilica particles and to ensure a homogeneous mixture, the homogenizer shear mixer shown in ‘figure 4’ was purchased especially for this study from IKA-WERK Company with rotational energy (mixing speed) 27,000 rpm. High engine speed in this study reduced the time consumed in mixing asphalt with additives and obtaining a homogenous blend of nanosilica composite modified asphalt.

Figure 3. Gradation of aggregate for surface course layer type IIIA.

Figure 4. Mixers types, mechanical mixer at the left and homogenizer mixer at the right.
4. Laboratory Work

4.1. Sample Preparation

To produce a nanocomposite polymer binder, by weight of bitumen, 2% of WPP with different percentages (0.5%, 1%, and 2%) of nanosilica was added to a preheated binder to 145°C. Initially, the mixing process started in a mechanical mixer. NS/WPP was adding together to a preheated binder and mixing them at a rotational speed 1370 rpm for 30 min at (165 ± 5)°C, then it transferred to a high shear mixing device has a rotational speed 27000 rpm at (165 ± 5)°C for 10 min to ensure homogeneity of the mix.

The optimum content of waste polypropylene (2%) was chosen depending on physical tests and Marshall stability which was performed in the laboratory for specimens of asphalt modified with different concentrations of waste polypropylene (1,2,3 and 5)% by weight of asphalt to produce WPP-modified asphalt. Polymer modified asphalt and nanosilica composite polymer modified asphalt specimens were subjected to asphalt traditional physical tests including penetration, softening point, and ductility as recommended by ASTM. The Marshall test was performed for control asphalt and both types of modified asphalt mixture samples (WPP, and NS/WPP) modified asphalt to estimate the mechanical performance of mixtures and study the effect of NS on asphalt modified with waste polypropylene polymer.

4.2. Tests

Conventional tests were performed for all types of binders and listed in (table 5).

4.2.1. Penetration Tests

Penetration test for control and modified asphalt binder samples as reported by ASTM D5[18] was carried out. The penetration test is used to evaluate the asphalt consistency and hardness, asphalt with higher penetration values indicating a softer degree of consistency. Penetration depth is measured in the unit of (0.1) mm.

4.2.2. Softening Point Test

As maintained by ASTM D36 [19] softening point test has been performed for control and modified binder samples. This test aims to determine the temperature at which the consistency of the asphaltic material has started to change and the tendency to flow.

4.2.3. Ductility Test

A ductility test is also performed on the asphalt specimens to measure tensile characteristics of asphaltic materials and indicate the cohesion of the asphalt cement binder. Asphalt binder with high ductility value is usually considered to have good low-temperature performance in service. The examination was done according to the standard (ASTM D1113) [20].

4.2.4. Rotational Viscosity Test (RV)

In general, the fluidity of the asphalt binder is measured by viscosity. The rotational viscosity aims to define the temperature that allows the asphalt mixture to reach and maintain the workability of asphalt and ensure the bonding between the components of the asphalt mixture during the mixing and compaction process. According to ASTM D4402 [21], the test was implemented using Brookfield Rotational Viscometer to determine the viscosity of each type of binder at 135 °C and 165 °C.

4.2.5. Marshall Stability and Flow Test

To understand the effect of adding NS particles and WPP polymer on the performance of asphalt mixtures, Marshall stability and flow have been implemented for asphalt mixture. For each type of asphalt binder, three samples of asphalt mixtures were prepared and inspected as specified in (ASTM D6927 – 15) [22]. The details of the Marshall tests are included in (table 6).
Table 5. Conventional tests for the control asphalt, (WPP, and NS/WPP) modified binders.

| Properties                  | Condition          | Control asphalt | 2% WPP | 0.5% NS/WPP | 1% NS/WPP | 2% NS/WPP |
|-----------------------------|--------------------|-----------------|--------|-------------|-----------|-----------|
| Penetration (0.1mm) @ 25°C  | 67                 | 49.1            | 38     | 35          | 28.3      |
| Softening point (°C) 5°C/min| 47                 | 54              | 54.5   | 58.75       | 61        |
| Ductility (cm) @ 25°C       | 140                | 133             | 135    | 137         | 138.5     |
| Specific Gravity @ 25°C     | 1.03               | 1.019           | 1.056  | 1.063       | 1.077     |
| Rotational Viscosity (Pa.sec)|       |                 |        |             |           |           |
| 0.135°C                     | 0.430              | 0.662           | 0.965  | 1.025       | 1.320     |
| 0.165°C                     | 0.128              | 0.155           | 0.212  | 0.222       | 0.271     |

Table 6. Marshall test results for mixture contain modified & unmodified asphalt binders.

| Mixture Type According to Additives | Ave. Marshall Stability, KN | Marshall Flow, mm | Average Bulk Density, g/cm³ | Air Void, % | MQ, [16] KN/mm |
|-----------------------------------|-----------------------------|--------------------|------------------------------|-------------|----------------|
| Control asphalt                   | 10.44                       | 3.2                | 2.342                        | 3.30        | 3.26           |
| 2% WPP                            | 12.77                       | 2.5                | 2.344                        | 3.62        | 5.11           |
| 0.5%NS+2% WPP                     | 13.03                       | 2.4                | 2.342                        | 3.86        | 5.43           |
| 1%NS+2% WPP                       | 13.20                       | 2.4                | 2.334                        | 4.03        | 5.50           |
| 2%NS+2% WPP                       | 14.01                       | 2.3                | 2.342                        | 4.37        | 6.10           |

5. Results and Discussions

5.1. Effect of Additives on the Consistency of Asphalt

‘Figures 5’ illustrates the influence of adding WPP and NS particles on the penetration value of asphalt (60-70) penetration grade. It can be noted that the penetration values decrease when adding waste polypropylene and different percentage of nanosilica. The decrease of the penetration value indicative of improving the rigidity of composite modified asphalt at high temperatures. These effects are mainly attributable to the diffusion and permeation of nanosilica powder in the asphalt binder, which helps to absorb light volatility material in the maltene portion and increase the asphaltene part of the asphalt binder [23].

Figure 5. Penetration results for control and modified asphalt.
‘Figure 6’ shows a difference in temperature of the modified and unmodified binders at the softening point. It could be seen that the temperature of the NS/WPP composite modified asphalt softening point increases with an increase in nanosilica content relative to the control and WPP-modified binders. The increasing trend in the softening point is an indicator of a reduction in temperature sensitivity which is perceived to have a beneficial effect on the rise in pavement resistance to low-temperature cracks and permanent distortion at high temperatures. These findings are imputing to the saturation of the nanosilica particles with the light volatile components of the asphalt and their conversion to resin in the asphalt fraction by NS. Also, the hardness of the NS/WPP composite modified binder is greater than that of the control and WPP modified asphalt binders, which leads to an increase in the rigidity of the improved asphalt binder [23].

5.2. Effect of Additives on Ductility
‘Figure 7’ exhibits the interrelation between ductility result and type of asphalt (WPP and NS/WPP). It’s clear from the results of this study that waste polypropylene decreasing the ductility whereas, the effect of waste polypropylene combined with NS increased the ductility values as the concentration of nano silica increased. This increase can be explained by that the addition of NS/WPP led to an increase in the flexibility of the asphalt, which reflects on the ability to recover after loading.
5.3. Effect of Additives on Rotational Viscosity (RV)

‘Figure 8 & 9’, reflecting the impact of WPP and the different percentages of NS on the asphalt control viscosity. It can be shown that all the additives have improved the viscosity value of the asphalt binder. It can also be shown that, as NS particles increases, the viscosity values have been improved. This increase is a consequence of the fact that the modified asphalt binder becomes stiffer, increased surface area, reactivity, and increased dispersion of NS in an asphalt binder material. It should be noted that the viscosity values obtained for the modified asphalt agree with the requirements in Superpave system specification 3 Pa.sec maximum. Asphalt with a high viscosity is suitable for road construction characterized by high traffic load.

![Figure 8. Rotational viscosity results of control and modified asphalt at 135°C.](image1)

![Figure 9. Rotational viscosity results of control and modified asphalt at 165 °C.](image2)

5.4. Effect of Additives on Marshall Stability and Flow

From the results listed in (table 6) and represented in ‘figure 10’, it is shown that the plastomeric polymer WPP and NS particles improve the performance of asphalt mixture. It can also be shown that Marshall stability values increase slightly as the NS percentage increases. In ‘figure 11’ the relationship between Marshall flow values versus the type of asphalt mixtures was shown. It can be seen that the increasing NS percentage has a positive effect on decreasing flow value more than WPP.
On the other hand, it can be seen that the Marshall quotient values obtained in this study and mentioned in (table 6) increased for asphalt mixtures modified using nanosilica composite polymer compared to asphalt mixture with control asphalt and modified asphalt using WPP polymer. The Marshall quotient is a method used to estimate the resistance of hot mix asphalt (HMA) to plastic deformation. In other words, it is the relationship between the value of Marshall's stability and its flow. This increase in the Marshall quotient indicates a decrease in permanent deformations in the hot asphalt mixture (HAM), i.e. NS particles improve the paving service life.

5.5. Effect of Additives on Air Voids

‘Figure 12’ shows the impact of additives on air voids percentage (%Va) in asphalt mixtures. It can be shown that the (%Va) increases for two types of additives, WPP and WWP/NS composite, and increases continuously as NS particles increases. Despite this increase, (%Va) has been within the required limit specifying (3-5) % as an allowable range. These results can be explained by the nanosilica particles absorbing a portion of the asphalt.
6. Conclusions
The following conclusions are drawn according to the study results
1. The penetrating value of the asphalt binder decreases when WPP-polymer has been added, and this decrease continues with the addition of NS particles, indicating increased hardness and stiffness at moderate temperatures of the NS/WPP composite modified asphalt.
2. The softening point of the NS/WPP composite modified asphalt is more than the softening point of the polymer-modified asphalt, indicating the hardness of NS/WPP composite modified asphalt binders are more than the WPP-modified asphalt due to the addition of NS particles.
3. Asphalt ductility decreasing with the addition of WPP polymer whereas it increased with an increasing percentage of nanosilica for NS/WPP composite binder, this implies an increase in asphalt elasticity with an increase in NS content and an increase in tension resistance.
4. In the Marshall experiment results, 2% of nanosilica particles with 2% WPP increased the stability test of Marshall by 34.2% and 9.71% compared with control and WPP modified asphalt binder, respectively, and an improvement in the Marshall quotient suggesting improved resistance to permanent deformations in the hot asphalt mixture.
5. It has been found that despite the rise in the percentage of air void, the limits of the standard have been preserved. The percentage increase in air voids was (32.4% and 20.72%) at 2% NS/WPP modified asphalt compared to control asphalt and WPP modified asphalt.

7. Recommendation
1. Perform other tests to evaluate performance characteristics such as fatigue and thermal cracks.
2. Carry out the SEM image to recognize the phases that were performed in the asphalt binder, and the depression of nanosilica powder in the modified binder.
3. Evaluate the (NS/WPP) composite-modified asphalt binder utilizing Optical Microscopy (OPM) and scanning electron microscopy (SEM) to evaluate the efficiency of modification is uniform or not.
4. Due to the possible risks to the respiratory system, safety systems and cautions must be enforced when using nanomaterials.

8. References
[1] Airey G D 2003 Rheological properties of styrene butadiene styrene polymer modified road bitumens Fuel
[2] Bala N, Napiah M and Kamaruddin I 2018 Effect of nanosilica particles on polypropylene polymer modified asphalt mixture performance Case Stud. Constr. Mater.
[3] Yusoff N I M, Breem A A S, Alattug H N M, Hamim A and Ahmad J 2014 The effects of moisture susceptibility and ageing conditions on nano-silica/polymer-modified asphalt mixtures Constr. Build. Mater. 72 139–47

[4] Zhu J, Birgisson B and Kringos N 2014 Polymer modification of bitumen: Advances and challenges Eur. Polym. J. 54 18–38

[5] Doğan M and Bayramli E 2009 Effect of polymer additives and process temperature on the physical properties of bitumen-based composites J. Appl. Polym. Sci. 113 2331–8

[6] Sadeque M and Patil K A 2013 Rheological properties of recycled low density polyethylene and polypropylene modified bitumen Int. J. Adv. Technol. Civ. Eng. 2 24–6

[7] Yao H, You Z, Li L, Lee C H, Wingard D, Yap Y K, Shi X and Goh S W 2013 Rheological properties and chemical bonding of asphalt modified with nanosilica J. Mater. Civ. Eng. 25 1619–30

[8] Risks S C on E and N I H 2006 Modified Opinion (after Public Consultation) on the Appropriateness of Existing Methodologies to Assess the Potential Risks Associated with Engineered and Adventitious Products of Nanotechnologies

[9] Li R, Xiao F, Amirkhanian S, You Z and Huang J 2017 Developments of nano materials and technologies on asphalt materials – A review Constr. Build. Mater. 143 633–48

[10] Shafabakhsh G H and Ani O J 2015 Experimental investigation of effect of Nano TiO2/SiO2 modified bitumen on the rutting and fatigue performance of asphalt mixtures containing steel slag aggregates Constr. Build. Mater. 98 692–702

[11] Arabani M, Tahami S A and Hamedi G H 2018 Performance evaluation of dry process crumb rubber-modified asphalt mixtures with nanomaterial Road Mater. Pavement Des. 19 1241–58

[12] Khatijah S, Bakar A, Ezree M, Abdullah M E and Asyiqin N 2017 Rheological and rutting evaluation of composite nanosilica / polyethylene modified bitumen Rheological and rutting evaluation of composite nanosilica / polyethylene modified bitumen

[13] Alhamali D I, Wu J, Liu Q, Hassan N A, Yusoff N I M and Ali S I A 2016 Physical and Rheological Characteristics of Polymer Modified Bitumen with Nanosilica Particles Arab. J. Sci. Eng. 41 1521–30

[14] Chrissafis K, Paraskevopoulos K M, Papageorgiou G Z and Bikiairis D N 2008 Thermal and dynamic mechanical behavior of bionanocomposites: fumed silica nanoparticles dispersed in poly (vinyl pyrrolidone), chitosan, and poly (vinyl alcohol) J. Appl. Polym. Sci. 110 1739–49

[15] Amini B, Rajabbolookat M J, Abdi A and Salehfarf R 2017 Investigating the influence of using nano-composites on storage stability of modified bitumen and moisture damage of HMA Pet. Sci. Technol. 35 800–5

[16] Hasaninia M and Haddadi F 2017 The characteristics of hot mixed asphalt modified by nanosilica Pet. Sci. Technol. 35 351–9

[17] Zghair H H, Joni H H and Hassan M S 2019 Impact of Mixing process on the physical and Rheological Characteristics of Asphalt Binder Modified with Nano-Silica Powder IOP Conference Series: Materials Science and Engineering vol 579 (IOP Publishing) p 12046
[18] ASTM D 2013 Standard test method for penetration of bituminous materials USA, ASTM Int.

[19] ASTM D 2014 Standard test method for softening point of bitumen (ring-and-ball apparatus) Am. Soc. Test. Mater. West Conshohocken, PA, USA

[20] D113 A 2007 Standard test method for ductility of bituminous materials Annu. B. Stand.

[21] ASTM D 2015 Standard test method for viscosity determination of asphalt at elevated temperatures using a rotational viscometer American Society for Testing and Materials

[22] ASTM A 2015 D6927-15 Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures ASTM Int. West Conshohocken, PA, USA

[23] Taherkhani H and Afroozi S 2016 The properties of nanosilica-modified asphalt cement Pet. Sci. Technol. 34 1381–6