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Multi Criteria Performance Analysis for Nano-Iron Oxide Modified Asphalt Cement by Using Fuzzy Promethee II

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Abstract. This study aimed to investigate the intermediate and high temperature performance characteristics of asphalt cement (AC) modified by iron-oxide nanoparticles (ION). Moreover, Fuzzy PROMETHEE-II technique was employed in order to evaluate the performance of base and ION modified AC by considering multiple criteria; physical properties, rheological characteristics, durability and economic aspects. Excluding the control sample (base AC); three different blends that contained 1%, 3% and 5% ION by the weight of AC were prepared. By conducting rheological testing procedures, isochronal plots were constructed and rutting and fatigue resistance parameters were evaluated. In addition to rheological properties, physical properties were also investigated under unaged and aged conditions and they were utilised in the Fuzzy PROMETHEE-II analysis. According to the experimental outcomes, the optimum concentration of ION was found to be 1% by the weight of AC at high temperatures and above this concentration the improvement of viscoelastic behaviour was hindered to due agglomeration. In other respects, addition of ION in the AC resulted in degrading of the elastic properties, meaning lower fatigue resistance against cracking. The findings of Fuzzy PROMETHEE-II also demonstrated similar trend of results with minor deviations indicating that, not only considering a single parameter but also as a complete ranking evaluation considering multiple criteria, the findings of the current study were reinforced.

Keywords. Asphalt raveling, system dynamics, material, system thinking

1. Introduction

Service life of flexible pavement roads relies on the performance characteristics of AC, which the pavement road is constructed. To overcome and mitigate the effects of climatic factors and vehicular loading, AC is expected to possess certain physical and rheological properties. These properties include; higher stiffness under low frequencies and high temperatures and higher elasticity in high frequencies and low and intermediate temperature conditions [1]. Modification of AC by common materials such as polymers, nanomaterials and polymer nanocomposites is a regularly employed process in the pavement industry to improve the performance characteristics of AC [2]. Particularly, nanomaterials have been favored to improve AC performance due to their

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versatile engineering features and numerous advantages over other alternative modifiers such as quantum effects and high surface area [3].

In the assessment of performance criteria for AC, penetration grading and viscosity grading have been adopted and still required by transportation agencies in terms of reference. However, these grading systems are single point measurements and they lack the attributes to sufficiently describe the viscoelastic behaviour of AC, which it is strongly dependent [4]. The advancement of experimental techniques has led to the adoption of dynamic shear rheometer (DSR) testing procedures, which enabled a more comprehensive assessment of its elastic and viscous behaviour [5].

The common testing procedures applied by a DSR are the frequency and temperature sweep tests although recently more advanced experimental techniques such as Multiple Stress Creep Recovery Test (MSCRT) are available [6]. The main reason for the customary adoption of frequency sweep tests is that, it can be applied both at intermediate and high temperatures. The outcomes of the frequency sweep test are the complex modulus (G*) and phase angle (δ) which represent the stiffness and elastic properties of AC respectively [7]. The results are displayed by constructing master curves, black diagram and isochronal plots. Furthermore, the rutting and fatigue resistance parameters are computed by using G* and δ outcomes [8].

Although, the viscoelastic behaviour of AC can be investigated by DSR, there is still need for conventional testing procedures in order to evaluate the physical properties of AC such as consistency, workability and aging resistance. Consistency and workability are important characteristics of AC, which presents the hardness and its mixability and pumpability during the production process [9]. Aging resistance is also a crucial index to determine the performance alterations during the construction and service life of the pavement [10].

Considering all the above-mentioned factors, it is not reasonable to determine the performance of AC by a single parameter. On this basis, a multi-criteria evaluation is required. One of the remarkable techniques for multi-criteria analysis is the Preference Ranking Organization Method for Enriching Evaluations (PROMETHEE) method [11]. The first use of the method dated back to 1982 and recently, it was advanced up to PROMETHEE-VI [12]. Although other versions are available, for the current study Fuzzy PROMETHEE-II was utilised due to its ability to provide a complete pre-order ranking [13]. Although, this method found its application particularly in social sciences, the Fuzzy PROMETHEE-II is emerging in the field of engineering and found its application in a number of civil engineering related research, which included the works conducted by Xiao and Zhang [14], Erdoğan and Kaya [15], Alas et al., [16] and Andrić and Lu [17].

2. Methodology

2.1. Materials and Sample Preparation

The materials used for the current study were 60/70 penetration grade AC and iron-oxide nanoparticles (ION) in the form of odourless brown powder and size of 70nm. In addition to a control sample, three different ION modified blends were prepared at the ratios of 1%, 3% and 5% by the weight of AC. The materials were heated to 165oC and blended together for 60 minutes with a high shear mixer at 5000 rpm to ensure fine dispersion of nanoparticles in the AC matrix. The testing procedures were conducted under fresh, short-term aged and long-term aged conditions. The short-term and long-term aging simulation of the base and ION modified AC were performed by using Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV) in accordance to ASTM D 2872 and ASTM D 6521 respectively.

2.2. Conventional Testing Procedures

The penetration and ring and ball softening point tests were conducted in accordance to ASTM D 5 and ASTM D 36 to evaluate the hardness and consistency of the base and ION modified AC. Additionally, rotational viscosity test (RV) was performed by using ASTM D 4402 to assess the workability of the blends, particularly to determine the convenient mixing and compaction temperatures.

2.3. Dynamic Shear Rheometer (DSR)

The frequency sweep test was performed in accordance to ASTM D 7175 by using a DSR. The tests were conducted under strain controlled condition within the linear viscoelastic region. The samples were tested in unaged, short-term aged and long term aged states. For unaged and short-term aged samples, sample size of 25mm diameter and 1mm thickness and for long-term aged samples, sample size of 8mm diameter and 2mm thickness were used. The testing frequencies ranged from 0.159 Hz to 15.92 Hz while the testing temperatures were between 4^{o}C-46^{o}C for PAV samples and 46^{o}C-82^{o}C for unaged and RTFO samples. Complex modulus (G*) and phase angle (δ) were the two parameters revealed by the tests. Isochronal plots were constructed to illustrate the elastic and vicious behaviour of the base and ION modified AC. Additionally, the rutting resistance and fatigue resistance parameters were evaluated by using the G* and δ results from the frequency sweep tests.

2.4. Fuzzy PROMETHEE-II

Fuzzy Preference Ranking Organization Method for Enrichment Evaluations (FPROMETHEE) is a multi-criteria decision making technique that employs an outranking approach to select the best alternatives from a limited set of options, considering the rankings established among a specific set of criteria [18]. The criteria set for the evaluation of performance of base and ION modified AC in the current study were based on; Rheological parameters (G* and δ), workability (rotational viscosity), durability (Aging index) and the economic aspects. Two different models for asphalt cement performance at intermediate temperature level between 4^{o}C-46^{o}C and high temperature level between 46^{o}C-82^{o}C were developed. The steps employed in the application of the Fuzzy PROMETHEE-II method were outlined in eq. 1 – eq. 8.

Step 1: Criteria specification (j=1,…k) and the set of possible alternatives.

Step 2: Weight determination.

$$\sum_{j=1}^{k} w_j = 1 \tag{1}$$

Step 3: Evaluation matrix normalisation.

$$R_{ij} = \frac{[x_{ij} - min(x_{ij})]}{[max\,(x_{ij} - min\,(x_{ij})]} \tag{2}$$

Where; x_{ij} is the judgments performed based on the evaluation measures provided.

Step 4: Determination of deviation by pairwise comparison.

$$d_j(a, b) = g_j(a) - g_j(b) \tag{3}$$

Where; $d_j(a, b)$ is the difference between evaluation of a and b for each criterion.

Step 5: Definition of preference function.

$$P_j(a, b) = F_j[d_j(a.b)] \tag{4}$$

Where; $P_j(a, b)$ is the function of the difference between the evaluation of alternative a regarding alternative b for each criterion.

Step 6: Calculation of multi-criteria preference index.

$$\pi(a, b) = \sum_{j=1}^{k} P(a, b)w_j \tag{5}$$

Step 7: Determination pf positive and negative outranking flows.

$$\emptyset^+(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a, x) \tag{6}$$

$$\emptyset^-(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x, a) \tag{7}$$

Where; $\emptyset^+$ is the positive outranking flow and $\emptyset^-$ is the negative outranking flow.

Step 8: Calculation of the net output flows

$$\emptyset(a) = \emptyset^+(a) - \emptyset^-(a) = \frac{1}{n-1} \sum_{j=1}^{k} \sum_{x \in A} [P_j(a, x) - P_j(x, a)]w_j \tag{8}$$

3. Results and Discussion

3.1. Physical Characteristics

The consistency and hardness of the base and ION modified AC were evaluated by using the penetration and softening point test results. As can be deducted from figure 1 and acquainted form the previously published research, the modification process has led to reduction in penetration and increase in the softening point values. A similar trend was also observed from the RV test results illustrated in figure 2. Increase in the ION content has resulted an increase in the RV. Since the increase in RV, results in a less workable mix and increases the energy required for pumping and mixing of the AC, it is preferable that lower RV achieved after the modification process. According to Liu et al., [19] the RV should not exceed 3 Pa.s at 135ºC. As depicted from figure 2, it was observed that although the modification process has led to increase in RV for the AC, the RV values are within the specified criteria to ensure fine workability for the asphalt mix.

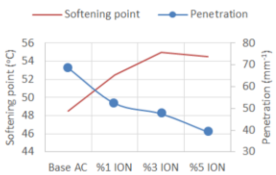

Figure 1. Pen and S.P for base and ION modified AC.

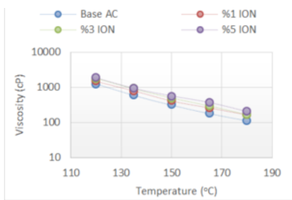

Figure 2. RV for base and ION modified AC

3.2. Rheological Properties

In order to represent the frequency sweep test outcomes, Isochronal plots were adopted. Isochronal plots represented the temperature dependent distribution of the viscoelastic properties for base and ION modified AC at specific frequencies of 0.159 Hz and 15.92 Hz, which were as illustrated in figure 3a and figure 3b respectively. It can be observed from figure 3a and figure 3b that, at both high frequencies and low frequencies, the addition of up to 1% ION in the base AC has resulted in increase in stiffness which is a suitable condition for AC to be used in climatic regions where high climatic temperatures are anticipated. Additionally, the trend line has shown that the variations of viscoelastic properties were more remarkable at elevated temperatures. The material behaviour change for AC modified by ION above 1% was also attributed to the uneven dispersion of nanoparticles inside the asphalt matrix.

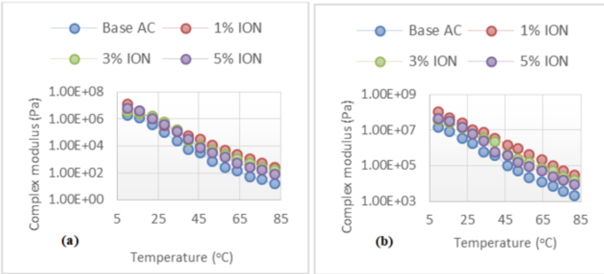

Figure 3. Isochronal Plots at 0.159 Hz (a) and 15.92 Hz (b).

Rutting (G*/sin δ) and fatigue resistance (G*x δ) parameters were calculated by using the outcomes of DSR tests. Higher G* indicated stiffer properties while higher δ indicated higher elasticity. The limiting values for unaged samples of AC for rutting and fatigue resistance parameters are 1kPa (min) and 5000kPa (max) respectively. The results presented in figure 4a showed that, base AC has achieved to pass beyond the limiting rutting value at around 64°C while ION modified AC were able to reach up to 76°C. The optimum performing modifier concentration was found to be 1% ION while above this concentration has led to reduced enhancement in rutting resistance parameter. On the other hand, it was observed from figure 4b that, the lowest fatigue resistance parameter was the unmodified sample, base AC and among the optimum performing ION concentration, 5% ION was the lowest for fatigue resistance.

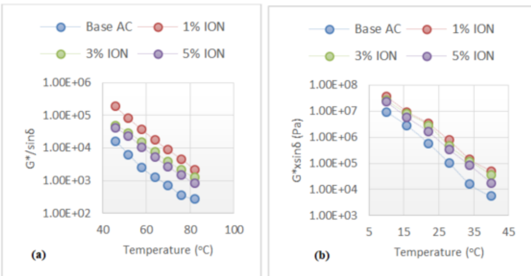

Figure 4. Rutting (a) and Fatigue (b) Resistance Parameters.

3.3. Fuzzy PROMETHEE-II

Fuzzy PROMETHEE-II method was utilised to evaluate the complete performance of base and ION modified AC based on a set of performance metrics rather than a single parameter metric. Among the parameters specified in calculating the net ranking included; physical properties, aging characteristics and rheological performance indicators. Two different models were developed; one for evaluating the overall performance at intermediate temperatures and the next for evaluating the performance at the high temperature ranges. The results of the net flow calculations for intermediate and high temperature performance were given in table 1 and table 2 respectively. It can be observed from table 1 that, considering a number of different parameters, the modification process undermined the performance of AC at intermediate temperatures due to losing elastic properties because of the modification process. On the contrary, results presented in table 2 showed that, 1% ION modified AC has superseded the other alternatives and ranked first by considering multiple criteria.

Table 1. FPROMETHEE-II net ranking for intermediate temperature performance.

	$\emptyset^{+}$	$\emptyset^{-}$	$\emptyset$	Ranking
Base AC	0.430	0.110	0.320	1
%1 ION	0.180	0.220	-0.04	3
%3 ION	0.290	0.180	0.110	2
%5 ION	0.100	0.490	-0.390	4

Table 2. FPROMETHEE-II net ranking for high temperature performance.

	$\emptyset^{+}$	$\emptyset^{-}$	$\emptyset$	Ranking
Base AC	0.080	0.470	-0.390	4
%1 ION	0.480	0.070	0.410	1
%3 ION	0.310	0.110	0.200	2
%5 ION	0.130	0.350	-0.220	3

4. Conclusion

The current research focused on experimental evaluation of ION modified AC and also adopted a multi-criteria analysis technique to finding the optimum performing ION concentration to modify AC. Experimental outcomes demonstrated that, a small amount of ION concentration up to 1% concentration has efficiently improved the rheological properties of AC particularly at high temperature performance characteristics. However, the enhancement in viscoelastic behaviour at intermediate temperature performance characteristics was undermined due to increase in stiffness and loss of elastic properties. Additionally, the results of the fuzzy PROMETHEE-II analysis presented consistent findings with minor distinctions. This suggested that the experimental results were not only verified by evaluating individual parameters but also by employing a comprehensive multi-criteria assessment approach.

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