The effects of reed fly ash modified bitumen on the volumetric and mechanical properties of open grade friction course mixtures

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Abstract. The global use of open grade friction course (OGFC) asphalt pavements began in 1950, though this practice has gained further interest over time, especially for high-speed high-volume roads, due to the material’s excellent characteristics in terms of skid resistance, drainage control, and noise reduction. Unfortunately, the porous structure of this type of mixture results in other problems related to mechanical and durability properties, despite extensive studies being conducted to overcome such problems using virgin modifiers such as polymers or fibres. Recently, the concept of using recycled and by-product materials as stabilising additives for asphalt binders and mixtures has became more popular, both in order to reduce the construction costs and to increase pavement service life, as well as preserving natural resources and reducing the environmental impact of construction. This study investigates the effect of using one such by-product material, reed fly ash (RFA), as a modifier for asphalt binder and to examine the performance of the resulting OGFC asphalt mixture. The effect of RFA on the OGFC mixture performance is examined in terms of volumetric (bulk density, air voids, porosity and permeability) and mechanical (indirect tensile strength (ITS), skid resistance, and Cantabro abrasion loss (CL)) properties. The results indicate that adding RFA to asphalt binder has a positive influence on mixture performance. In terms of volumetric measures, it leads to increases in air voids, porosity, and permeability of about 17\%, 37\%, and 102\%, respectively at 18\% RFA, while the bulk density is reduced as RFA dosage increases. Simultaneously, mechanical properties are increased, with ITS and skid resistance increased by about 10\% and >25\%; respectively at 18\% RFA. However, the resistance to abrasion was enhanced only at lower dosages of RFA (6\% RFA), by about 36\%. Nevertheless, the use of RFA at optimal percentages appears to offer a sustainable approach to stabilising asphalt binder for OGFC mixtures.

Keywords: porous asphalt mixtures; fly ash; recycled materials; by product materials; modified asphalt binder.

1. Introduction

Open grade friction course (OGFC) pavements consist of an overlay layer placed over existing dense graded asphalt mixture (DGAM) at a thickness ranging between 19 and 50 mm; they are characterised by high amounts of coarse aggregate, while the volume of fines is low or even absent [1-4]. This type of structure provides a high volume of air voids, ranging between 15\% and 25\% [5, 6]. The use of OGFC asphalt mixture as an alternative to DGAM began in 1950 [7, 8] due to its advantages, especially when
used on high-speed, high-volume roads, in terms of environmental considerations, safety, anti-skidding resistance, and noise reduction [9-11]. In addition, the high air voids content of this type of asphalt mixture contributes to minimising water risks in terms of: spray and splash, and reducing the risk of aquaplaning by allowing the permeation of water through the porous skeleton [12, 13]. However, the high air void content, in association with the use of neat binder, can make the mixture highly sensitive to water and oxygen, resulting in reduced adhesion between the aggregate and binder within the paving layer that can make the mixture subject to raveling.

Interest in modification concepts for asphalt binders and mixtures has increased with time, and various types of virgin modification materials have been suggested [14]. Among these materials, the focus has often been on various types of polymers, such as Styrene Butadiene Styrene (SBS), Styrene Butadiene Rubber (SBR), and Ethylene Vinyl Acetate (EVA) [15, 16] or fibres, such as cellulose fibre, polyester fibre, and mineral fibre, [9, 17]. Recently, the highway building community has begun to investigate the use of sustainable materials, such as recycled and by-product materials, in order to increase the lifespan of pavements, reduce overall costs, and preserve natural resources [18-23]. The application of a modification process using polymers, whether virgin or recycled, has found to cause a series of physical and chemical changes in the bitumen structure and mixture. In terms of physical properties, the addition of modification materials to asphalt binder generally leads to reinforcement of the asphalt, as it provides crosslinking through the binder colloidal system. Simultaneously, from the chemical properties perspective, the use of these materials helps in change the asphalt polarity, often enhancing adhesion and cohesion characteristics [24-26].

These mechanics of polymer enhancement have encouraged researchers to investigate the effects of by-product fly ashes on the rheological properties of asphalt and the mechanical properties of asphalt binders or mixtures. Various studies, as conducted by Sharma et al. [27], Cai et al. [28], Xue et al. [29], and Arabani et al. [30], have reported that the use of ashes such as rice husk ash enhance the thermal sensitivity, ductility, viscosity, complex modulus, and rutting resistance of asphalt binder. In addition, improvement of asphalt mixture performance in terms of moisture damage, stiffness, stability, hardening, and tensile strength has been observed, though negative influences on mixture resistance to thermal and fatigue cracking have also been noted [31]. Other studies investigating the effect of ashes such as rice husk ash and palm kernel shell ash used as filler replacement have found that these have a positive effect on mixture stability, tensile cracking, fatigue resistance, moisture damage and rutting resistance. In 2016, a study conducted by Foroutan et al. [32] demonstrated the effect of date seed ash (DSA) on the chemical composition of asphalt binder; incorporating of DSA into asphalt binder made it harder and denser due to the presence of silica particles in the chemical composition of the ash that created cross-linking between the asphalt binder and DSA particles. That study also reported that the presence of oxidation compounds in the chemical composition of DSA made it susceptible to reacting with aliphatic chains and polar groups in the colloidal system of the asphalt binder, forming weak carboxylic acid chains that enhanced the basic properties of asphalt, increasing the stiffness of the asphalt binder. As a result of this reaction, a waterproofing film is formed on the aggregate surface that may help increase the resistance of the asphalt mixture to water damage [32].

Based on this concept, this study aimed to investigate the use of another type of biomass by-product material, Reed Fly Ash (RFA), as an asphalt modifier and to study its effect on the volumetric and mechanical properties of OGFC asphalt mixture. Reeds grow widely throughout Iraq, near drains and marshes, and the burning of this plant for energy generation or disposal creates ashes that have previously resulted in increased environmental pollution problems. Trials of the use of the resulting ashes as a modifier for asphalt binder or other construction materials may thus help reduce these effects problems, as well as potentially leading to reduced construction costs and adding to the understanding of the effects of such materials on the behaviours of asphalt mixtures.
2. Materials

2.1 Aggregate

Crushed limestone aggregate was supplied from an aggregate quarry located in Karbala, Iraq, and used to develop OGFC mixtures. The physical properties and gradation of aggregate used are summarised in table 1. Two types of fillers were used: conventional mineral filler (CMF) and hydrated lime (HL), with equal amounts of each added; their properties are displayed in table 2. HL was used in such a large dosage to control water sensitivity.

Table 1. Aggregate gradation and stone-on-stone contact verification.

| Sieve size, mm | Used gradation/Percent passing, % | ASTM D7064/D7064M [33]Percent passing, % |
|----------------|----------------------------------|------------------------------------------|
| 19.00          | 100                              | 100                                      |
| 12.50          | 92.5                             | 85 – 100                                 |
| 9.50           | 47.5                             | 35 – 60                                  |
| 4.75           | 17.5                             | 10 – 25                                  |
| 2.36           | 7.5                              | 5 – 10                                   |
| 0.075          | 3                                | 2 – 4                                    |

Physical properties of aggregate

- Bulk specific gravity of coarse aggregate: 2.600 C127
- Bulk specific gravity of fine aggregate: 2.642 C127
- Water absorption of coarse aggregate (%): 2.25 C127
- Water absorption of fine aggregate (%): 2.42 C127
- Los Angeles abrasion (%): 25.5 C131

Table 2. Filler properties.

| Element     | Concentration (CMF) | Concentration (HL) |
|-------------|---------------------|--------------------|
| SiO₂        | 81.89               | 0.89               |
| Al₂O₃       | 3.78                | -----              |
| Fe₂O₃       | 1.92                | 2.25               |
| CaO         | 7.37                | 90.58              |
| MgO         | 3.45                | 3.60               |
| K₂O         | 0.73                | 0.58               |
| Na₂O        | 0.19                | 1.00               |
| Bulk density (gm/cm³) | 2.65 | 2.3 |
| Surface area (m²/Kg)   | 223            | 1450              |

2.2 Bitumen

Neat bitumen with a 40 to 60 penetration grade was adopted in this study for the design of the OGFC asphalt mixture. For the modified bitumen, RFA was used in this study in three dosages: 6%, 12% and 18% by bitumen weight. The properties of the bitumen before and after modification are illustrated in table 3.

Table 3. Physical properties of bitumen before and after modification.

| Property                  | ASTM Specification | Neat bitumen | 6% RFA | 12% RFA | 18% RFA |
|---------------------------|--------------------|--------------|--------|---------|---------|
| Penetration at 25 °C      | D 5-5a             | 43.5         | 31.4   | 29.8    | 27.8    |
| Softening point (R&B °C)  | D 36-95            | 49.6         | 52.6   | 53.5    | 56.5    |
| Ductility at 25 °C (cm)   | D 113-99           | 132          | 126    | 115     | 105     |
2.2.1 Reed fly ash (RFA)
The reed fly ash used in this investigation was supplied from local drainage banks, and was subjected to two burning processes. The first was conducted on site to reduce the size of the reeds; this was done at approximately 450 °C. A muffle furnace was then used to achieve the requirements of the second burning process, particularly the calcination phenomenon; this burn was done at 950 °C for two hours, as suggested by previous researchers [22]. Thereafter, the burned reeds were ground using a mechanical grinder for one hour to develop ash with micro-size particles. Figures 1 and 2 show the scanning electron microscopy of the reeds fly ash and the shape of reed particles during the preparation steps, while table 4 outlines the properties of RFA.

| Viscosity, c. stokes at 135 °C | D 4402-02 | 868.9 | 951.5 | 1056.0 | 1115.6 |
|--------------------------------|-----------|-------|-------|--------|--------|
| Penetration index (PI)         | Read et al.[34] | -1.605 | -1.550 | -1.452 | -0.958 |

Table 4. Physical properties of RFA.

![Scanning electron microscopy of reed fly ash.](image1)

![Steps of preparation of reed fly ash.](image2)

3. Laboratory work

3.1 Preparation of modified bitumen
Three dosages of RFA were used in this study to modify the penetration grade bitumen, being 6%, 12% and 18% by weight of bitumen. These adopted dosages of RFA were selected within the range used by other researchers such as Foroutan et al. [32] and Arabani et al.[30]. RFA was added gradually to bitumen previously heated to 150°C in a mixer container, and the blending process was continued at 1,500 rpm for 30 min in a shear mixer with continuous heating until a homogeneous mix emerged.

3.2 Preparation of mixture
Two types of samples were fabricated in this investigation to study the effects of modification on the performance of OGFC mixtures: Marshall specimens with dimensions 63×100 mm, which were compacted using a Marshall hammer, with 50 blows to each face; and slab samples, required for the skid resistance test, with dimensions 300×165×50 mm, created using a vibratory compactor procedure.
as recommended by BS EN 12697-22 [35]. The control mixture (CM) adopted in this study had an optimum asphalt content (OAC) of 6.2%, as recommended by ASTM D6932/6932M [36] and following the procedure described in ASTM D7064/D7064M [33].

3.3 Volumetric properties
Bulk density (BD), air voids (AV), porosity, and permeability were determined for CM and RFA modified OGFC mixtures in accordance with ASTM D3203/D3203M [37], ASTM D7064/D7064M [33], Putman et al. [38], and ASTM D5084 [39], respectively. Table 5 summarises the information gathered to calculate these parameters.

Table 5. Parameters required for volumetric property computation.

| Parameter          | Equation/ Criteria for determination | Computation parameters                                                                 | Number of required samples |
|--------------------|--------------------------------------|----------------------------------------------------------------------------------------|----------------------------|
| Bulk specific gravity | $G_{mb} = \frac{W_{dry}}{V \times \rho_w}$ | $W_{dry}$: dry weight of compacted specimen. $V$: total volume of compacted specimen. $\rho_w$: density of water. | 2                          |
| Air voids          | $V_a = \left(1 - \frac{G_{mb}}{G_{mm}}\right) \times 100$ | $G_{mb}$: bulk specific gravity of compacted specimen. $G_{mm}$: maximum theoretical specific gravity. | 2                          |
| Porosity           | $P_o = \left(1 - \frac{W_{dry} - W_{sub}}{\rho_w V_T}\right) \times 100$ | $W_{dry}, W_{sub}$: dry and submerged weight of compacted specimen. $V_T$: total volume of compacted specimen. | 2                          |
| Permeability       | $K = \frac{aL}{At} \ln \left(\frac{h_1}{h_2}\right)$ | $(K)$ is permeability, $(A)$ is the cross-sectional area of the specimen, $(a)$ is the cross-sectional area of the stand pipe, $(L)$ is the height of the specimen, $(t)$ time required to water to flow through the sample, $(h_1)$ the head above the sample surface equal to 365 mm, $(h_2)$ the head above the sample surface equal to 140 mm. | 4                          |

3.4 Mechanical properties
Indirect tensile strength (ITS), skid resistance, and Cantabro abrasion loss for CM and RFA modified OGFC mixtures were determined in accordance with AASHTO T283 [40], ASTM E303 [41], and ASTM D7064/D7064M [33], respectively. Table 6 summarises the information gathered to calculate these parameters.

Table 6. Parameters required for mechanical property computation.

| Parameter                  | Equation/ Criteria for determination | Computation parameters                                                                 | Number of required samples |
|---------------------------|--------------------------------------|----------------------------------------------------------------------------------------|----------------------------|
| Indirect tensile strength | $ITS = \frac{2000P}{\pi t D}$       | $ITS$: tensile strength, Kpa, $P$: maximum load, $N t$: specimen thickness, mm, and $D$: specimen diameter, mm. | 3                          |
| Skid resistance           | British Pendulum Number (BPN)        | rubberized slider passing a standard between 124 mm and 127 mm distance that is specified on the slab surface is recorded | 2                          |
\[ CL = \frac{P_1 - P_2}{P_1} \times 100 \]

\( (CL) \) is Cantabro loss, \( (P_1) \) weight of sample before abrasion, and \( (P_2) \) weight of sample after abrasion.

4. Results and discussion

4.1 Volumetric properties

Figures 3 to 6 show the results for volumetric properties for all types of OGFC asphalt mixture in terms of bulk density, air voids, porosity, and permeability. The results show that the proportions of air voids and porosity increase as RFA dosage increase, in increments ranging from 5% to 17% and 10% to 37%, respectively. The density level appears to display adverse behaviour as RFA content increases, decreasing proportionately. The reasons for these variations lie within the physical and chemical changes that occur on adding RFA to asphalt binder. From a physical properties perspective, the porous nature and high surface area of RFA absorb a large amount of the light molecular weight components of asphalt, while chemical changes are created by the incremental increase in asphaltene adhesive polar effects due to the polar nature of the RFA material and the presence of silica particles from the chemical composition of RFA, as seen in table 4, which help reinforce the bitumen structure by increasing the crosslinking between bitumen molecules. All these factors tend to make the asphalt binder stiffer and more viscous, as can in table 3, as a result of increases in adhesion. Moreover, these reactions also lead to increases in the stability and thickness of the asphalt film coating the aggregate, resulting in an increase in both air voids and porosity. This increment in air voids means that the magnitude of bulk density decreases as RFA content increases, as illustrated in figure 3, due to the increase in volume and decrease in weight of mixture. Shen et al. [23], Ahmadinia et al. [42], and El-Naga et al. [43] all showed similar trends for air voids, porosity, and bulk density.

![Figure 3. Bulk density of CM and RFA modified OGFC mixtures.](image1)

![Figure 4. Air voids of CM and RFA modified OGFC mixtures.](image2)
In terms of permeability property, the results of the laboratory tests are summarised in figure 6 for both CM and RFA modified OGFC asphalt mixtures. These results show that the ability of an open structure to permit the flow of water is enhanced after including RFA into the mixture. The addition of RFA to the mixture helps gradually increase the permeability level of the OGFC mixture, by up to 102% more at the higher dosage of RFA than seen in CM. This is associated with corresponding increases in the stability of the binder film, as mentioned previously, as these reactions combine to increase the stability of asphalt film coating aggregate, as well as reducing the number of voids filled with asphalt, thus increasing the porosity of the OGFC mixture, in agreement with Shen et al. [23] and Qian et al. [44].

4.2 Mechanical properties

4.2.1 Indirect tensile strength

Figure 7 illustrates the results of testing the indirect tensile strength of CM and RFA modified OGFC asphalt mixtures. The results indicate that the use of RFA as an asphalt modifier leads to a slight enhancement in the resistance of mixture to tension as the RFA dosage increases, reached about a 10% increase on CM. The reason for this enhancement is the increment of asphaltene adhesive with the chemical composition of the asphalt due to the polar nature of RFA, which increases the viscosity of the asphalt binder, along with the presence of silica particles within the RFA material that make the bitumen stiffer, as mentioned previously; together, these result in an increase to the thickness of the asphalt film coating the aggregate, which along with the effects of the physical properties of RAF, results in improvements to the tensile properties of the mixture. The micro-spreader particle system and lower cementitious properties of RFA material offer only slight reinforcement to the asphalt, however, as reflected by the mixed performance in terms of tensile cracking resistance. Foroutan et al. [32] discovered similar trends in their study using date seed ash (DSA).
4.2.2 Skid resistance
The effect on the roughness properties of OGFC asphalt mixture of using RFA as an asphalt modifier is illustrated in figure 8. These results suggest that mixtures modified with RFA materials have rougher surfaces compared with the CM in both dry and wet cases. Figure 8 shows that incorporating RFA into the mixture helps increase the BPN level to above 25% in both wet and dry cases as compared with CM. This is related to the increase in asphalt binder viscosity due to the polar nature of RFA that helps in increase the asphalt binder stiffness, as reflected in the macrotexture stability of the aggregate particles and the improved volumetric properties, which cause the roughness of OGFC pavement to increase. Figure 8 also shows that the BPN in greater in the dry case than the wet case, which can be attributed to the presence of water on the pavement surface (surface of slab sample) in the wet case, which works to reduce the friction between the vehicle tire (sliding rubber) and the pavement surface; as a result, friction forces decrease, and, consequently, BPN levels also decrease. The behaviours of these mixtures were also in agreement with the findings obtained by Shen et al. [23], Adamu et al. [45], and Chen et al. [46].

![Figure 8. Skid resistance of CM and RFA modified OGFC mixtures.](image)

4.2.3 Cantabro abrasion loss
The results for Cantabro loss for all types of OGFC asphalt mixture are illustrated in figure 9. The results indicate that the effect of using RFA as a modifier for asphalt binder decreases the OGFC mixture’s ability to withstand degradation, leading to an increase in the loss of mixture as the RFA dosage increases; even lower dosages only satisfy the specification requirements with no improvements seen. This arises from the nature of the micro-spread particles and the lower cementitious properties of RFA material, which offer little reinforcement for asphalt binder. In addition, the large surface area of this material makes it more susceptible to agglomeration, especially at higher dosages of RFA, which makes the mixture brittle and more exposed to breaking. Figure 9 shows that the amount of abrasion of OGFC mixture modified with RFA remain lowers than that of CM due to the increment in asphaltene adhesive, along with the presence of silica particles in the chemical compounds of RFA material; these factors lead to an increase in thickness of the asphalt film coating the aggregate, as well as an increase in asphalt film stability, reducing abrasion. Shirini et al. [47] and Abduljabbar et al. [21] noted similar behaviours with regard to Cantabro loss.
5. Conclusion
The aim of this study was to investigate the effect of including a by-product RFA material as a stabilising additive in the asphalt binder used for OGFC mixture. From the results obtained by laboratory testing, the following points can be concluded:

1. Incorporating 18% RFA by weigh resulted in increases to both air void proportion and porosity of OGFC asphalt mixture, by about 17% and 37%, respectively.
2. With regard to bulk density, the utilisation of RFA in OGFC mixtures leads to a decrease in mixture density of about 3% at 18% RFA by weight.
3. Incorporating high dosages of RFA into OGFC mixture leads to an increase in the ability of the mixture structure to infiltrate water of about 102%.
4. RFA modified OGFC mixtures perform slightly better than CM, nearly 10%, in terms of ITS, being measured at 18% RFA.
5. In terms of resistance to skidding in OGFC asphalt, this was enhanced in both dry and wet conditions by more than 25% by adding the RFA modifier at 18% dosage.
6. The abrasion loss properties of the OGFC mixture showed adverse effects at high dosages of RFA, while lower dosages merely met specification requirements.

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