Evaluating the Effect of Porous Concrete Pavement Characteristics on Beneath Pavement Layers

A A Abdulwahid 1, N T Al-Shafi’i 2 and Sh F Al-Busultan 3

1 MSC, Dept. of Highway and Transportation Eng., University of Al-Mustansiriyah, Baghdad, Iraq- aliadnan1994aa@gmail.com.
2 Assist Prof. Dr., Dept. of Civil Engineering, University of Al-Mustansiriyah, Baghdad, Iraq, dr.nagham_tariq@uomustansiriyah.edu.iq: naghamtariq95@gmail.com
3 Assist Prof. Dr., Dept. of Civil Eng., University of Kerbala, Karbala, Iraq, s.f.al-busultan@uokerbala.edu.iq

Abstract: The significance of the porous concrete pavement arises from the fact that it has the dual function of supporting traffic and stormwater management, in addition to many other characteristics such as minimizing noise and minimizing reflected heat. The goal of this study is to reveal more understanding of the stress-strain ratio of the porous concrete pavement and the layers beneath it. This process was done through two stages namely: laboratory stage by characterizing porous concrete mixtures (normal, and others sustainable mixtures comprised Reed Fly Ash and/or Silica Fume), and simulation stage by using a simulation program (ABAQUS) to identify the stress-strain induce an according traffic load within pavement layers. However, within the scope and materials used, the obtained results showed that the stresses within pavement layer are highly related to upper layer thickness, material types, and stiffness. Also, the main conclusion is demonstrated where there is optimum thickness (20 cm) of the porous concrete layer, which induces the minimum stress-strain in various layers of the pavement system.

Keywords: Compressive Strength; Porous Concrete; Reed Fly Ash; Silica Fume.

1. Introduction
The cities over the world are being covered with structures and the airproof concrete pavement; thus, the natural resources of rainfall water are increasingly wasted. As a result a lot of planning is inspected by researchers to conserve and return the normal ecosystems around the world. Pervious concrete or porous concrete is well known as one of the key elements of low-impact sustainable development. Currently porous concrete is one of the most hopeful sustainable materials because it is high porosity and permeability. It is considered as an alternative to conventional impervious concrete pavements for controlling the running water environmentally and economically [1]. The porous concrete can be considered as a type of lightweight
concrete, which can be achieved by eliminating the fine aggregate (sand) from the normal concrete mix. Because it is high air-voids, porous concrete generally has notable lower mechanical strength and durability properties as compared to those of traditional concrete [2] [5]. The porous concrete pavement can offer a dual function of supporting traffic and stormwater management. Nowadays and due to fast acceleration both in-vehicle characteristics and modern high functional classification of highways, the average operation speed increased rapidly. Accordingly, the level of noise increases noticeably, causing unacceptable noise pollution. Many researchers have suggested porous concrete as a vital solution to this problem: [6].

The Finite Element Analysis method (FEA) provides a powerful technique to find a solution for problems involving the behavior of structures subjected to loads, accelerations, displacements, or variation in temperature. The use of 3D FEA methods for analyzing concrete pavements subjected to mechanical and environmental loads has developed increasingly in the last decade. The increased use of Three-dimensional (3D) FEA has given pavement designers and researchers best understanding of critical portion of pavement response that cannot be determined with the analytical solutions, such as concrete pavement joint load transfer, [7], the influence of concrete pavement slab support on stresses, [8], in addition to the pavement response under dynamic loads, [9]-[10]. The ease with FEA dealing with complex geometry, boundary conditions, and material characteristics had encouraged designers and researchers to use comprehensive FEA programs such as SLAB-49 by [11], ILLISLAB by [12], JSLAB by [13], and PMAPR by [14]. Zaghloul and White, [15], and Zaghloul et al. [16] used ABAQUS program, a 3D FEA tool for concrete pavement analysis. Mallela and George, [17] reported successful employment of the ABAQUS program in improving simplified response models for uncracked concrete pavements.

2. Research Aim and Scope
The main aim of this research is to understand the developing stress-strain in porous concrete pavement layers using a simulation program approach. This was done by two stages:

- **Laboratory stage**, which focused on identifying the modulus of elasticity of the porous concrete with different mixtures properties, namely: normal previous mixture, a mixture comprising silica fume, and mixture comprising Silica Fume (SF) with partial replacement of cement with Reed Fly Ash (RFA).
- **Simulation stage**, which was implemented to develop the understudying process of the relationship between stress-strain for different porous concrete pavement slab thickness and stiffness.

However, such a development plan is restricted by some parameters such as The mixing ratios of the porous concrete and the types of additives to improve the porous concrete pavement.

3. Experimental Program

3.1 Materials

3.1.1 Cement. Iraqi Sulfate Resistance Cement (SRC), Type V, from a local supplier manufactured at Tasluja Cement Plant, was used in all mixtures throughout this research work. The chemical and physical properties of the cement were determined according to the requirement of the Iraqi specification [18]. The chemical properties are shown in table 1.
Table 1. Chemical Properties of the RFA as Compared with those of SF and SRC.

| Chemical composition | RFA | SF    | SRC  |
|----------------------|-----|-------|------|
| CaO                  | 3.10| 1.22  | 60.76|
| SiO₂                 | 82.24| 90.65 | 19.39|
| Fe₂O₃                | 0.31| 0.01  | 5.01 |
| Al₂O₃                | 7.06| 0.02  | 4.38 |
| MgO                  | 0.59| 0.01  | 3.21 |
| K₂O                  | 1.70| 0.14  | 0.59 |
| Na₂O                 | 0.88| 0.23  | 0.13 |

3.1.2 Coarse Aggregate. One type of crushed gravel coarse aggregate with (4.75 to 12.5) mm particle size was used. The sieve analysis of the aggregate particles is shown in Table 2.

Table 2. Sieve size Analysis of the Used Coarse Aggregate.

| Sieve size (mm) | Percent Passing |
|-----------------|-----------------|
| 12.5            | 100             |
| 11.2            | 99.81           |
| 9.52            | 97.81           |
| 8               | 77.73           |
| 4.75            | 0               |

3.1.3 Silica Fume (SF). Silica Fume was a dark blue color and had a soft texture. The chemical and physical properties of the utilized SF conform to the requirement of ASTM C1240, [19]. The chemical properties are shown in Table 1.

3.1.4 Reed Fly Ash. In this work, a new type of fly ash materials was produced and used as a partial replacement of cement to increase the sustainability of the porous concrete. This new type of fly ash was produced from reeds, which is available widely in the middle and southern of Iraq. The process of producing is adopted from a research study conducted by Zain et al. [20]. The process to create this type of fly ash is as follows, the first step involved reduction of the volume of the reeds by burning in open air to make it possible to inter the lab combustion furnace. The reed ash produced from the first step was entered the Lab combustion furnace by using dish heat resistance for 2hr at a temperature of 800 °C. Table 1 shows the chemical properties of the RFA.

3.1.5 Superplasticizer. A new generation of superplasticizer was incorporated as the chemical intensifier in this research study. Visocrete super E4-SIQ was used in the mixing to achieve the desired workability (slump) of the fresh concrete and reduce the water to cement ratio. The superplasticizer is conforming to ASTM C-494, [21].

3.2 Mixtures Matrix
To achieve the aim of this research work, the matrixes of the planed mixtures are classified into three types, and the percentage of the different variables is determined as it is shown in table 3 below.

3.3 Test methods.
To identify the objective of this research work, the following test methods are chosen:

3.3.1 Modulus of Elasticity. To determine the modulus of elasticity of the porous concrete, (100*200) mm cylinder was casted and cured for 28 days. This test was conducted according to ASTM C469-02, [22]. Figure 1 shows the procedure for testing the modulus of elasticity of the porous concrete.

3.4 Simulation Preparation
The 3D model was created by the ABAQUS program to simulate the stress-strain relationship at various slab thicknesses as it is shown in figure 2. This model consists of three layers (porous concrete, subbase, and subgrade), the thickness of the slab is varied between (15, 20 and 25) cm, while that of the subbase and subgrade soil is between 25 cm and 75 cm, respectively. The dimension of the model is 1m in width and 2.02m in length. This model surface is divided into two slabs by contraction joint with the dimension of 1m in width and 0.02m in length, and it is thickness dependson the thickness of the slab concrete, according to Huang, [23]. Which is (0.0375, 0.05, 0.0625) m, and it sealing by asphalt material with a constant dimension 1m in width and 0.02 in length and 0.01 in thickness. Table 4 shows the modulus of elasticity and tension ratio of each material, the modulus of elasticity for porous concrete was extracted from the laboratory tests, but tension ratio was adopted from Huang, [23], for the sealing asphalt and the (subbase, subgrade) layer, while the modulus of elasticity was taken from other research, [24]-[26].

In this study, dual-wheel axle load was adopted to simulate the applied load on the pavement surface, because the model dimension is small, just one side of the dual wheel axle load will be taken in this study as shown in figure 2. According to Yoder and Witczak, [27], the standard wheel load applied on the

### Table 3. Ratios of Mixing for all Stages.

| Type of mixtures | Mixture code | C/CA | W/C | SF/C | RFA/C | SP/W |
|------------------|--------------|------|-----|------|-------|------|
| Normal           | A1           | 20%  | 25% | -    | -     | -    |
|                  | A2           | 20%  | 30% | -    | -     | -    |
|                  | A3           | 20%  | 35% | -    | -     | -    |
|                  | A4           | 10%  | 30% | -    | -     | -    |
|                  | A5           | 30%  | 30% | -    | -     | -    |
| Silica fume      | B1           | 20%  | 25% | 10%  | -     | 1%   |
|                  | B2           | 20%  | 25% | 15%  | -     | 1.2% |
|                  | B3           | 20%  | 25% | 20%  | -     | 1.4% |
| Reed fly ash     | C1           | 20%  | 27% | 20%  | 8%    | 1.4% |
|                  | C2           | 20%  | 30% | 20%  | 16%   | 1.4% |
|                  | C3           | 20%  | 34% | 20%  | 24%   | 1.4% |

*a C/CA (cement/coarse agg).
*b W/C (water/cement).
*c SF/C (silica fume/ cement).
*d RFA/C (reed fly ash/cement).
*e SP/W (superplasticizer/water).
The applied load of each tire is considered equal to 20 kN, and it distributed uniformly over the total contact area on the pavement surface. According to Huang, [23], the tire pressure on the contact area ranges between (550 and 700) kPa, so the tire pressure is considered equal to 550 kPa for each tire. After doing the calculation, the dimension of the tire contact area on the pavement surface will be (158*230) mm. The clear spacing between the two-tier for each side of the dual wheel axle load is 184 mm C/C.

For all three models that would be created and analyzed, the approximate element size or mesh size was 0.03 m for all porous concrete slab thickness while it was 0.05 m for asphalt sealing material, 0.2 m for the subbase layer, and 0.4 m for subgrade layer. The coefficient of friction between the concrete and subbase is 0.15, while there is full contact between subbase and subgrade is full contact. The bottom of the model was fixed, which means that there is no movement or rotation in any direction. The sides of the subbase and subgrade soil were fixed and allowed to move in any direction. The sides of the porous concrete slab were allowed to move in any direction except the z-direction and the rotation in the y-direction. figure 2 represents the boundary conditions of the model.

![Figure 1. Modulus of Elasticity Test for Porous Concrete.](image1)

![Figure 2. 3D Diagram for the Simulation Process.](image2)

**Table 4. The Materials Properties Used in the Model.**

| Type of Materials   | Type of Mixtures | Elastic Modulus (KPa) | Poisson’s Ratio |
|---------------------|------------------|-----------------------|-----------------|
| Porous concrete     | N\(^a\)          | 16,228,000            | 0.15            |
|                     | S\(^b\)          | 23,639,000            | 0.15            |
|                     | F\(^c\)          | 23,575,000            | 0.15            |
| Mastic asphalt      | -                | 02,500,000            | 0.30            |
| subbase soil        | -                | 123,000,00           | 0.35            |
| Subgrade soil       | -                | 41,360,000            | 0.40            |

\(^a\) N is normal porous mixture.

\(^b\) S is a silica fume porous mixture.

\(^c\) F is a reed fly ash porous mixture.
4. Results and Discussion

4.1 Laboratory Side

For normal mixtures as those shown in figures 3 and 4, the compressive strength (stress) increases as the W/C ratios increase and it is the same for C/CA mixtures, because of the internal structure of the normal porous concrete is weak, due to the weakness of the cement paste which is responsible of covering and binding all the coarse aggregate together. When the cement paste increase, more aggregate will be covered, and the thickness of cement paste around aggregate will increase. The connection lines between the aggregate will also increase. As mixtures are comprising silica fume, when the SF/C increases, the strength of the cement paste increases as a result of the positive role of the silica fume, as can be seen in figure 5. Concerning mixtures comprising silica fume and reed fly ash, when the RFA/C ratio increases the strength of the cement paste will decrease due to the replacement of more active material by pozzolanic less active material, as it can be seen in figure 6.

![Figure 3. Stress-Strain Relationship for Varies W/C Ratios.](image-url)
Figure 4. Stress-Strain Relationship for Varies C/CA Ratios.

Figure 5. Stress-Strain Relationship for Varies SF/C Ratio.
4.2 Simulation Side.

4.2.1 Stress Distribution. For all porous concrete slab thicknesses, the behavior of the three porous mixtures that have been studied is almost have the same trend with some variation in their values, because they have a different modulus of elasticity, as it is shown in figures 7, 8, and 9. For pavement system with 15 cm slab thickness, a portion of the applying stress on the pavement surface will transfer to the underlying soil layers, especially to the subbase layer, because the thickness of the porous concrete slab is very low and it is too weak to resist the applying stress, as it is shown in figures 7. For pavement system with 20 cm slab thickness, the slab of porous concrete will carry the most of the applying stress, as it is shown in figures 8. The stresses on the slab concrete is high and the stresses on the subbase and subgrade layers are comparatively low in contrast to the slab with a pavement system with 15 cm thickness. For pavement system with 25 cm slab thickness, the vertical stress approximates the same vertical stress on 20 cm porous concrete slab thickness as it is shown in figure 9; this reveals that approximately 20 cm thickness neutralizes the effect of vertical stress.
4.2.2 Strain Distribution

The behavior of the three porous concrete mixtures strain is the same for all porous concrete slab thickness with some variation in their values as it is shown in figures 10, 11, and 12. For the pavement system with 15cm slab thickness, the strain at the top and bottom of the concrete slab is too low, but the strains increase in the sub base and subgrade layers because they have a lower modulus of elasticity as it is shown in figure 10. For pavement system with 20cm slab thickness, the strength of the porous concrete slab increases, so the strain of the underlying layers must decrease, but the weight of the slab has applied additional load to the soil layers as it is shown in figure 11. For pavement system with 25cm slab thickness, the strain in the soil layers decreases because the slab has absorbed most of the applying stress as it is shown in figure 12.

Figure 9. Vertical Stress Distribution Over 25cm Slab Thickness for Varies Porous Concrete Pavement Mixtures.

Figure 10. Vertical Strain Distribution Over 15cm Slab Thickness for Varies Porous Concrete Pavement Mixtures.
5. Conclusions
The study cues up with the following conclusion
1. The modulus of elasticity for normal porous concrete is weak, but it becomes better when the connection between the aggregate particles becomes stronger. However, optimum strength can be obtained by introducing Silica fume with 20% of the weight of cement content.
2. Replacing 8% of the 20% of the silica fume offers a mixture with a close modulus of elasticity to the modified mixture.
3. High stresses will transfer to the beneath layers when the low pervious concrete pavement layer thickness is used.
4. Moderate slab thickness can offer the best solution to minimize the transfer stresses to the beneath pavement layers. Within the scope of this research work, a 20cm slab thickness is the base slab thickness of the porous concrete pavement.
5. The self-weight of slab thickness adds more stresses if the over required thickness is adopted. Within the scope of this research work a 25cm slab thickness showed an increase in the stresses and strains of the beneath pavement layers.

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Figure 11. Vertical Strain Distribution Over 20cm Slab Thickness for Varies Porous Concrete Pavement Mixtures.

Figure 12. Vertical Strain Distribution Over 25cm Slab Thickness for Varies Porous Concrete Pavement Mixtures.
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