Mechanical strength and hydraulic properties of modified porous concrete mixtures

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Abstract. This study presents a comprehensive experimental investigation on the behavior of porous concrete mixtures intended to be used as surface road layer containing mineral admixture. Silica fume and/or fly ash were used to formulate modified concrete mixes at ratios ranged from 10% to 20%. A systematic change in 50% of the 9.5 mm aggregate particles size was adopted throughout single size coarse aggregate of 5mm. This in turn produces two groups of concrete mixes and eight individual mixtures. The compressive and tensile strengths, voids content and permeability characteristics were measured and the obtained results were compared with relevant guide of porous concrete. The results showed that a moderate strength of 24 MPa can be obtained at early ages. For the same concrete mixture, the values of voids content and permeability were 21.7% and 19.3 mm/s, respectively. Such kind of concrete can be used in construction of roads and it helps in water draining purposes.

Keywords: porous concrete, mineral admixtures, road pavement, permeability feature.

1- Introduction

In recent years, it became an important to develop road pavements to cover the sharp increase in both population and the traffic load. From the urban design point of view, roads are an important factor in the upgrading of the worldwide economy. They provide movement of peoples and goods efficiently in a safe manner with saving in both time and money. On the other hand, the environmental problems began to grow steadily such as runoff, water pollution, noise and high temperatures in urban territories.

One of the main problems facing road pavements is the accumulation of water on its upper surface. Recently, a new formulation of concrete was studied to address the problems caused by the action of water on the surface of rigid pavement based on the idea of draining out the water to the underlying layers. The new generation of such development is so called “porous concrete”. This kind of concrete comprises materials to form high porosity using cement, coarse aggregate, little or no sand, admixtures and water [1]. The behavior of porous concrete mainly depends on the type of cement and the maximum size of coarse aggregate are used. The latter component (i.e aggregate) has an important role on both strength and
permeability aspects. The term permeability which is the major criteria for the porous concrete refers to the ease which the water can passage through the concrete element [2].

Since it is formulated with a minimum amount of cement and with little or no fine aggregate portion, porous concrete considers a lightweight concrete with a density in a range of 1900 Kg/m³. In addition, it is considered as a pavement layer with low cost and possessing lower drying shrinkage and thermal conductivity. Consequently, it has great features in different respects. However, it has own restrictions need to be taken in consideration. For instant, some studies pointed out that the porous concrete is limited to be used in parking lots, minor roads and sidewalks. The reason for this is attributed to the lower strength resulting from high air voids. Basically, the bulk structure of porous concrete is formulated when a thick layer of cement paste surround the particles of coarse aggregate which knows as interfacial transition zone that result in air voids content ranging from (15 to 35)% [3, 4]

Despite the high percentage of voids that lead to a weakening of concrete strength compared to normal concrete, porous concrete acquired high attention in research works nowadays. This is due to many advantages that make it used in several applications such as water absorption, heat reduction, noise reduction, increased safety by increasing the friction force between car tires and the pavement surface as well as pollution reduction [5].

This study focuses on how to produce a modified porous concrete possessing both high mechanical strength and porous structure. This was proposed by using cementitious materials as a partial substituted for the cement paste combined with a systematic change in the grading of the coarse aggregate with existence of the chemical admixture for the plasticizing purposes.

2- Experimental Program
2.1 Materials used
A Portland cement type V produced by Al-Jesr plant was used for preparation all concrete mixes. It has physical and chemical properties consistent with the Iraqi Standard No: 5/1984 [6]. Silica fume type MegaAdd MS (D) was used as a pozzolanic supplementary material for the Portland cement with ratios of 10% and 12.5%, respectively. These percentages were selected after reviewing number of previous studies and avoiding the negative effects associated with the high percentage of replacement and complied with the limitations of the ASTM C1240 [7]. Fly ash type C was also adopted as a partial substitution for the Portland cement at ratios of 15% and 20%, respectively. These ratios were used for the same reason mentioned above for choosing the content of silica fume and it was consistent with the requirements of ASTM C618 [8]. Tables 1 and 2 show the chemical properties of the Portland cement, silica fume and fly ash used in this study with the limitations of their relevant standards.

Crushed gravel with two particle sizes was used as a coarse aggregate. The reference concrete mixes were formulated with graded coarse aggregate of 5-19 mm. Four modified concrete mixes were incorporated single size gravel of 5 mm replaced instead of the sieves of 9.5 mm and 12.5 mm at ratios of 50% and 100%, respectively. The results of sieve analysis for the coarse aggregate used are shown in Table 3. And Figure 1. It is satisfied with the requirements of Iraqi Standard No: 45/1984 [9].

Due to the fact that porous concrete has a lower compressive strength, Hyperplast PC 200 was used as a high performance super plasticizing admixture to enable the water content of the mix to perform more effectively. Flocrete SP42 was also used as a retendering admixture to control the setting time of the concrete mixes. Both of the former chemical admixtures were consistent with the ASTM C494 specifications [10].
### Table 1. Chemical and physical properties of Portland cement type V

| Property                        | Values | ASTM(C1240) Limitation | Values | ASTM(C618) Limitation |
|---------------------------------|--------|-------------------------|--------|-----------------------|
| Lime Saturation Coefficient     | 0.94   | 0.66 – 1.02             |        |                       |
| Magnesium Oxide (MgO) %         | 3.21   | < 0.5                   |        |                       |
| SO₃ Content %                   | 2.1    | <2.5                    |        |                       |
| Loss on Ignition %              | 3.5    | <4                      |        |                       |
| Insoluble Residue %             | 0.77   | <1.5                    |        |                       |
| Tricalcium Aluminates (C₃A) %   | 3.14   | 2.4 - 3.1               |        |                       |

### Table 2. Properties of silica fume and fly ash used in this study

| Property                        | Silica Fume | Fly Ash |
|---------------------------------|-------------|---------|
| Color                           | Grey powder | Off White |
| Specific gravity                | 2.3         | 2.10 to 2.40 |
| Silicon Dioxide (SiO₂) %        | 90.6        | Minimum 85% |
| Moisture Content (H₂O) %        | 0.58        | Maximum 3% |
| Loss on Ignition (LOI) %        | 2.86        | Maximum 6% |
| Specific surface area           | 21          | Minimum 15 m²/g |
| particles retained on 45        | 7           | Maximum 10% |
| micron sieve                    |             | 12       | Maximum 34% |
| Specific gravity                | 2.23        | >2.2     |
| Compressive strength of cement  | 16.4        | >15      |
| (MPa)                           | (7 days) (MPa)| 27     |
| (MPa)                           |             | >23      |

### Table 3. Sieve analysis of the coarse aggregate used with the limitations of the IQS. No.45-1984 [6]

| Sieve opening size | Passing% | Iraqi Specifications No.(45 L.S. No-451984) |
|--------------------|----------|------------------------------------------|
| 19 mm              | 95       | 95-100                                   |
| 12.5 mm            | 45.78    | -                                        |
| 9.5 mm             | 30       | 30-60                                    |
| 4.75 mm            | 1.9      | 0-10                                     |
| 2.36 mm            | 1        | -                                        |
2.2 Selection of mix proportion and mixing procedure

After reviewing several papers and previous studies, a suitable mix design was chosen to produce the reference porous concrete mix with a grade of strength 20 MPa at 28 days age [11]. In order to obtain the target of this study, five modified concrete mixes were formulated using the techniques of incorporating mineral additives and chemical admixtures associated with reducing the size of aggregate particles for the sieves of 9.5 mm and 12.5 mm. Table 4 shows the details of the reference and modified concrete mixtures produced in this study.

Table 4. Mix proportions of the porous concrete mixtures

| Material   | Group A (mixes with coarse aggregate size of 5-19mm) | Group B (mixes with replacing sieve 9.5 mm with 50% of single sized aggregate of 5mm) |
|------------|--------------------------------------------------|----------------------------------------------------------------------------------|
|            | A1  | A2 | A3 | A4 | B1 | B2 | B3 | B4 |
| Cement     | 425 | 371.8 | 340 | 318.7 | 425 | 371.8 | 340 | 318.7 |
| Gravel     | 1335 | 1335 | 1335 | 1335 | 1335 | 1335 | 1335 | 1335 |
| Water/cement ratio | 0.29 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 |
| Sand       | - | - | - | - | - | - | - | - |
| Silica fume | - | 53.12 | - | 42.5 | - | 53.12 | - | 42.5 |
| Fly ash    | - | 85 | 63.75 | - | - | 85 | 63.75 | - |
| Hyperplast PC 200 | - | 4.25 | 4.25 | 4.25 | 4.25 | 4.25 | 4.25 | 4.25 |
| Flocrete SP42 | - | 2.125 | 2.125 | 2.125 | 2.125 | 2.125 | 2.125 | 2.125 |
In order to produce the porous concrete mix, high attention has been paid for the issue of workability since it considers as a zero-slump concrete and usually expected to be segregated. As for the mixtures containing superplasticizer, multi trial mixes were performed to adjust the optimal water content that gives balance between the features of strength, workability, permeability and voids ratio specified for the porous concrete in the relevant codes of practice [12].

For the mix procedure, all sides of the mixer machine were wetted to ensure that no part of the mixing water is lost during the mixing process. All ingredients were then mixed in dry status to obtain a homogenous constituent. The superplasticizer admixture was premixed with the mixing water and two third of the combined volume was gradually added to the batch. After mixing for about 3 minutes, the residual one-third of the mixing water was then added. This in turns give a homogenous composition for concrete mix. All of the concrete samples were then casted, compacted and covered with nylon sheet for 24 hours. Then after, the samples were demolded and kept in the water at ± 20 C until the date of test. The aforementioned procedure complied with the requirement of the BS EN.

2.3 Test Methods
In order to determine the properties of reference and modified porous concrete mixes, the following aspects have been investigated.

2.3.1 Compressive strength
The compressive strength test was performed on cube specimens according to the ASTM C39/C39M [13] using universal compression machine with capacity of 200 MPa. The load was increased with a loading rate of 0.5 MPa/second until failure. The test was carried out at two ages 7 and 28 days and the average values of three samples was taken for each test.

2.3.2 Voids content
This test was performed based on the instructions of the ASTM C175/C175M [14] using cylinder specimens. Firstly, the specimens were dried out to constant mass in an oven and then immersed in water to determine the volume of solids. Voids content was calculated using the difference between the total volume and displaced volume of the submerged specimens as per in Eq.1

\[
\text{Void Content} = \left[ 1 - \left( \frac{K \times (A - B)}{\rho_w \times D^2 \times L} \right) \right] \times 100
\]

where, A is dry mass of specimen (g), B is the submerged mass of the specimen (g), D average diameter of specimen (mm), L average length of specimen (mm), K is a factor (1273240) in SI unit and \( \rho_w \) is density of water (kg/m³). Water balance was used in this test, as shown in Figure 2.

2.3.3 Coefficient of permeability test
This test was carried out based on the concept of falling head method according to the ACI 522R-10 [11] as shown in figure (3.b) that measures the height of water during the time unit, but instead of height, the volume will be measured using the device shown in Figure (3.a) because it gives a clearer discharge than the height .The test was made inside the lab at ambient temperature of the Lab (i.e. 25°C±1). The permeability coefficient can be calculated through equation below [15]:

\[
K = \frac{V \times L}{h \times A \times t} \quad \text{(mm/s)}
\]

Eq. (2)
Where, $V$ is volume of discharge in Liter, $L$ length of specimen (mm), $h$ is column height (885mm), $A$ is the area of the specimen (mm$^2$) and $t$ represents time for discharge in seconds.

Figure 2. Water balance used in the voids content test

Figure 3. Permeability test device
3- Results and discussions

3-1 Mechanical behavior

Table 5 shows the results obtained for the compressive and tensile strengths at 7 and 28 days age for groups A and B concrete mixes. It can be seen that a moderate strength of 22 MPa has been obtained for the reference porous concrete (Mix A1) at 28 days ages. The average strength development at 28 days relative to that recorded at 7 days for this mix was 1.3. The former value seems to be lower than that usually achieved for the normal concrete at 1.5. For the modified porous concrete mixes of group A, the highest compressive strength was noted for the Mix A3 in which 20% Portland cement was replaced by fly ash followed by Mix A2 then Mix A4. The corresponding compressive strength values were 23.8, 21.59 and 13.3 MPa, respectively. The later concrete mix (Mix A4) did not satisfy the strength requirement for the structural concrete.

In regard to the relative strength between 7 and 28 days ages, the recorded values were 1.2, 2 and 1.11 for the concrete mixes A2, A3 and A4, respectively. Such behavior can be explained by the filling role and covering mechanism of the mineral admixtures which may take further period of time to appear. As the mechanical failure is normally governed by the weakness point in addition to free sand nature of this kind of concrete, so there is a high potential for existing weakness surfaces within the interfacial transition zone. Such justification appears in the fractures cube samples as shown in Figure 4. Similar results have also been obtained by [16, 17] The aforementioned studies mentioned that the mineral admixtures can cover the microstructure of concrete and enhancing the mechanical strength at later ages. Unclear behavior was noted at early ages.

For the systematical change in the maximum size of concrete performed for group B mixes, Mix B4 reveals the highest strength value of 23.1 MPa at 28 days age. The reason for that may be related to more fineness coarse aggregate particles available in addition to the higher surface area of the mineral admixtures used for this mix. All of the concrete mixes of group B showed range of 1-1.2 strength development at 28 days ages compared with those at 7 days.

For the results of splitting tensile strength, similar tendency to that observed for the compressive strength was noted for both of porous concrete groups. In general, lower tensile strength was obtained when the mineral admixtures are used. This is an indication for the preliminary coating behavior at this period of curing time.

| Test type                    | Curing age | (A1) | (A2) | (A3) | (A4) |
|------------------------------|------------|------|------|------|------|
| Average compressive strength | 7 days     | 16.6 | 18   | 12   | 11.9 |
| strength (MPa)               | 28 days    | 22   | 21.59| 23.8 | 13.3 |
| Average tensile strength     | 7 days     | 3.1  | 2.15 | 1.24 | 1.17 |
| strength (MPa)               | 28 days    | 3.17 | 2.3  | 1.33 | 1.74 |

| Test type                    | Curing age | (B1) | (B2) | (B3) | (B4) |
|------------------------------|------------|------|------|------|------|
| Average compressive strength | 7 days     | 21.75| 9.9  | 14.19| 20   |
| strength (MPa)               | 28 days    | 22.15| 12.1 | 15.48| 23.1 |
| Average tensile strength     | 7 days     | 1.75 | 1.48 | 2.95 | 1.21 |
| strength (MPa)               | 28 days    | 1.84 | 1.61 | 2.7  | 1.81 |
Table 6. Result of void content and permeability of porous concrete.

| Test type       | Group A |          |          |          |          | Group B |          |          |          |          |
|-----------------|---------|----------|----------|----------|----------|---------|----------|----------|----------|----------|
|                 | Curing age | (A1) | (A2) | (A3) | (A4) | (B1) | (B2) | (B3) | (B4) |
| Voids ratio (%)| 7 days   | 21.4 | 24.2 | 27 | 29 | 17.6 | 16.5 | 14.1 | 19 |
|                 | 28 days  | 18 | 19 | 21.7 | 23 | 19.34 | 17.5 | 8.96 | 20.4 |
| Permeability (mm/s) | 7 days | 25.72 | 23.1 | 21.04 | 23.15 | 23.15 | 21.04 | 11.5 | 17.8 |
|                 | 28 days  | 21.04 | 21 | 19.3 | 19.3 | 19.3 | 19.3 | 7.71 | 15.43 |

Figure 4. Failure modes of porous concrete cube samples under compression loads

3.2 Voids content and permeability

Table 6 shows the results obtained for the voids content and permeability at 7 and 28 days age for groups A and B concrete mixes. It can be seen that both of voids content and permeability aspect reduces with the time. This was expected as the hydration of cement increases, the volume of capillary pores decreases and disconnected with the solid hydration products. The highest value of voids content was recorded for the mix A3 at 21.7%. The use of mineral additives as substitution for the Portland cement has an effect on the hydraulic properties and since the particles of these additives are much smaller than the cement particles used, they will fill in the spaces between the cement particles as it leads to reducing the size of these voids and the areas of their contact with each other by preventing their fusion and thus the concrete structure will restrict void size distribution.

Since the reference mixtures (A1 and B1) are free from any kind of additives, the concrete structure has large voids and thus allows more water to pass through. The correct behavior of the additives in general
does not reveal at early ages because the reactions of these additives are slow pozzolanic reactions and need more time. However, acceptable values for the voids contents and permeability were obtained when the mineral admixtures are used.

The systematic change in the maximum size of coarse aggregate (i.e. replacing the aggregate size of 9.5 mm by 5 mm) has obvious effect on reducing the voids content. The ratio of voids content still within the range suggested for the effective porous concrete indicated as (15 to 35%). The same can be said for the permeability feature in which the discharge value exceeded the limit indicated for such type of concrete (i.e 1.0 to 47.7 mm/s) [1, 18].

4. Conclusions

This study was undertaken to investigate the mechanical and hydraulic behavior of modified porous concrete intended to be used as surface road layer. The critical findings can be summarized as follow:

1. Structural and permeable porous concrete was obtained throughout optimizing between the maximum size of coarse aggregate and mineral admixtures.
2. The behavior of concrete mixes containing silica fume and/or fly ash is governed by the coating role and the chemical activity of such additives appears at later ages.
3. The mechanical strength of porous concrete mixes highly depends on the microstructure of the Interfacial Transition Zone (ITZ) between the cement past and coarse aggregate particles.
4. Both of voids content and permeability aspect showed reduction with the time and further reduction was also noted when 50% of 9.5mm coarse aggregate particles are substituted with single size particles of 5mm.
5. Based on the boundary conditions of this study, the porous concrete mix containing 20% fly ash showed the optimization between the strength and draining characteristic as it reveals the heights value of compressive strength (24MPa) and suitable values of voids content and permeability of 21.7% and 19.3 mm/s respectively. Long term behavior may need for investigation.

References

[1] Xu G, Shen W, Huo X, Yang Z, Wang J, Zhang W and Ji X 2017 Investigation on the properties of porous concrete as road base material Construction and Building Materials 158 141-8
[2] Cosic K, Korat L, Ducman V and Netinger I 2015 Influence of aggregate type and size on properties of pervious concrete Construction and Building Materials 78 69-76
[3] Sonebi M, Bassuoni M and Yahia A 2016 Pervious concrete: mix design, properties and applications RILEM Technical Letters 1 109-15
[4] Chindaprasirt P, Hatanaka S, Charerat T, Mishima N and Yuasa Y 2008 Cement paste characteristics and porous concrete properties Construction and Building Materials 22 894-901
[5] Tamai H 2015 Enhancing the performance of porous concrete by utilizing the pumice aggregate Procedia Engineering 125 732-8
[6] I.Q.S 1984 Portland Cement Specification
[7] ASTM 2020 Standard Specification for Silica Fume Used in Cementitious Mixtures ASTM C1240-20 ASTM International West Conshohocken, PA
[8] ASTM 2019 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete ASTM C618-19 ASTM International West Conshohocken, PA
[9] Iraqi Specification No.5/1984, Aggregate from Natural Sources for Concrete and Construction Central Organization for Standardization and Quality Control Baghdad
[10] ASTM 2019 Standard Specification for Chemical Admixtures for Concrete ASTM C494 / C494M-19 ASTM International West Conshohocken, PA

[11] ACI Committee 522. 2010 Specification for Pervious Concrete Pavement American Concrete Institute.

[12] Jimma B E 2014 Workability-integrated mixture proportioning method for pervious concrete

[13] ASTM 2020 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens C39 (West Conshohocken, PA: ASTM International)

[14] ASTM 2012 Standard Test Method for Density and Void Content of Hardened Pervious Concrete C1745 ASTM International West Conshohocken, PA

[15] Batezini R and Balbo J T 2015 Study on the hydraulic conductivity by constant and falling head methods for pervious concrete Revista IBRACON de Estruturas e Materiais 8 248-59

[16] Hassan K E, Cabrera J G and Maliehe R S 2000 The effect of mineral admixtures on the properties of high-performance concrete Cement and concrete composites 22 267-71

[17] Khan S U, Nuruddin M F, Ayub T and Shafiq N 2014 Effects of different mineral admixtures on the properties of fresh concrete The Scientific World Journal 2014

[18] Elizondo-Martínez E-J, Andrés-Valeri V-C, Jato-Espino D and Rodríguez-Hernandez J 2020 Review of porous concrete as multifunctional and sustainable pavement Journal of Building Engineering 27 100967