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Technical Evaluation of Using Grouting For Producing Semi-Flexible Asphalt Concrete Mixtures

تقييم فني لإستخدام الحقن لإنتاج المخلوطات الأسفلتية الشبه مرنة

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الملخص

حدث نقص ملحوظ في الاسفلت المعروض في السوق المصري نظرا للكم المتزايد لمشروعات إنشاء الطرق خلال العقد الحالي مما أدي الي إستيراد الاسفلت من الخارج فتفاقمت مشكلة العملة الصعبة وتزايدت أسعاره المحلية. هناك مشكلة أخرى خطيرة و هى انه قد لوحظ إنتشار التخدد علي عدد كبير من الطرق المصرية المنشأة حديثا نظرا لزيادة نسبة مركبات نقل البضائع و زيادة الأحمال المحورية بسبب زيادة الاعتماد على النقل البرى للبضائع. بالتالي أصبح من الضروري البحث عن حل يكفل إستحداث رصف أسفلتي ذا محتوي أقل من الاسفلت و قدرة أعلي لمقاومة التخدد. تهدف هذه الدراسة إلي توصيف و تصميم نوع من الخلطات الاسفلتية ذات محتوي أسفلتي قليل نسبيا و مقاومة أعلي للتخدد بغرض الإستخدام في تنفيذ الطبقات السطحية. لتحقيق أهدف الدراسة تم اللجوء إلي إسلوب حقن قوالب مارشال للخلطات الاسفلتية العالية النفاذية المنتجة بتأثير طاقات دمك مختلفة باستخدام مواد حقن محلية. أستخدم الحجر الجيرى و رمل ناتج الكسارات و بودرة الحجر الجيرى لاعداد خلطات عالية النفاذية و حسبت نسبة الاسفلت التصميمية للخلطات الواقعة تحت الفحص نظريا. أعدت قوالب مارشال للخلطات و تم حقنها بالاسمنت و مخلوط الاسمنت و الرمل السليسى بنسب مختلفة ثم أجريت عليها إختبارات الضغط الغير محاط و الثبات و الشد الغير مباشر للتعرف علي خصائصها الهندسية كما أجريت نفس الاختبارات علي خلطة تقليدية ذات تدرج 4 ج بنفس المواد لاستخدام نتائجها للمقارنة. بين تحليل نتائج البحث فاعلية تكنولوجيا الحقن بكل من الاسمنت البورتلاندي العادي ومخلوطه مع الرمل ناعم بنسبة 1:1 في توفير مايقرب من 35 الي 44% من كمية الاسفلت المطلوبة ورفع مقاومة الخلطات العالية النفاذية للتخدد من خلال زيادة مقاومة الضغط و الثبات بما يعادل 3 أضعاف القيم المناظرة للخلطات الاسفلتية التقليدية.

Abstract

A noticeable shortage was occurred in the asphalt supply in the Egyptian Market due to the increasing volume of road construction projects in the current decade, which led to importing asphalt from foreign countries. Consequently, aggravates the problem of hard currency and increasing the local asphalt prices. Another serious problem has been also observed on unlimited number of newly constructed Egyptian roads, that is the rutting distress due to the increasing of both of percentage of goods truck and axle loads accompanied by the increasing of goods transported via the Egyptian highway networks. So, finding out a solution to develop mixtures that have lower asphalt contents and high resistance to the rutting becomes essential. This study aims at characterization and design special type of asphalt mixture having lower asphalt content and of higher rutting resistance to be used in paving surface layers. To achieve this objective, grouting technique of highly permeable asphalt mixtures produced under different compacting efforts was used. Crushed limestone, crushed sand, and limestone filler were used to prepare highly permeable asphalt mixtures. Asphalt contents of these mixes were determined theoretically. Marshall moulds representing these mixes were prepared and grouted using ordinary portland cement (OPC) as well as mixtures of OPC and silica sand with different ratios. Unconfined compressive strength (UCS), Marshall Stability, and indirect tensile strength tests were conducted on these mixes to define their characteristics. The same tests were conducted on crushed limestone traditional mix of 4C gradation for comparison purposes. Analyzing the study results, the active effect of grouting technique using each of OPC as well as mixture of 1: 1 OPC and silica sand was concluded. Reduction from 35% to 44 % of the required asphalt amount and increasing of rutting resistance for highly porous mixes through increasing UCS and stability by about 3 times compared with traditional asphalt mixtures.

Keywords

Porous asphalt mixtures, Grouted macadam, Semi-flexible pavement, Rutting.

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1. Introduction

Egyptian government expanded in construction of new roads in the last few years to meet the requirements of the economic growth. The local production of Egyptian 60/70 asphalt cement is currently insufficient. About 20% of asphalt is imported to cover the needs of the local asphalt market. This increases the problem of hard currency in Egypt and rapidly increases the asphalt prices. The asphalt price has been increased from 80 E.P/ton at 1991 to 1112 E.P/ton in 2008. The asphalt prices reached 4607 E.P/ton in 2015 [1]. Another problem has been noticed. Actual axle loads using Egyptian roads network highly increased from 6 to 7 tons for steering axle, from 10 to 13 tons for single axle-dual wheel, and from 16 to 20 tons for tandem axle [2]. The affected tire pressures also have been increased from 80 psi to 140 psi [3][1] [3]. This phenomenon worsens the pavement deformation, mainly rutting distress. A comprehensive study indicated that rutting is the most widely spread distress in Egypt. About 36.8% of the Egyptian road lengths are suffering from rutting [4]. Untraditional solution is required to solve all these problems.

This study aims to producing asphalt concrete mixtures having lower asphalt contents and higher rutting resistance. The solution was to use semi flexible asphalt concrete mixtures. Through reviewing, such mixtures were found in the literature under many different names such as grouted macadam, semi-flexible pavement (SFP), asphalt-Portland cement concrete composite (APCCC), resin modified pavement (RMP), combi-layer, cement-filled porous asphalt (CFPA). Also, packed manufactured grouts were produced under various commercial names such as Salviacim, Densiphalt, Confalt and EucoPave. Semi flexible asphalt concrete mixture is basically an open-graded (porous) asphalt concrete mixture containing 25 to 35 percent voids filled with cement slurry grout. The two materials are produced and placed separately. The production of the materials and the mixture requirements for both the open-graded asphalt mixture and the slurry grout are modified and differ slightly from conventional procedures [5]. The SFP is generally 2 inch thickness. The open graded asphalt mixture is placed with standard paver but is not compacted. After placing, the pavement surface is simply smoothed with a small steel wheel roller, generally a 3-ton maximum. Compaction of the open graded asphalt mixture will adversely decrease the voids and binder grout penetration [6]. Although grouted macadam is not very well documented in the literature but has a rather long history. In the early 1950s Salviacim was introduced in France with the purpose to protect the asphalt concrete wearing course against deterioration due to oil and fuel spillage. The cement slurry penetrated only about 10 mm into the asphalt concrete at this stage. The good resistance to rutting was then discovered as a positive side effect [7]. As the construction of grouted macadam has developed, it has many applications including bus stations, port pavements, industrial and warehouse floors, airport platforms, taxiways and runways, brake and acceleration strips at traffic lights and bridge deck overlays [7, 8, 9]. SFP usage has been spread through into several countries such as Europe, Africa, the South Pacific, the Far East, Malaysia and North America [10], but it has not been used in Egypt yet. The reasons for choosing grouted mixtures can be summarized as achieving fuel and oil resistance, creating flexible pavement compared by portland cement concrete pavement (PCCP), reducing constructions efforts and costs as well as maintenance costs compared to PCCP, sustaining high loads and preventing rutting, improved life cycle costs compared to both flexible and rigid pavements and avoiding joints [7, 8, 11].

To achieve the study objectives, asphalt mixes having air voids between 25 and 40% were prepared at different level of compaction. The investigated mixes were grouted using only OPC and fine sand.

Additives like plasticizer, fly ash, and silica fume usually used in grouting. It is not recommended to investigate in this study due to its expensive cost in Egypt. The physical and mechanical properties of grouted mixtures were evaluated on the base of the corresponding properties of traditional dense asphalt mixture.

2. Experimental Design

To achieve study objectives, a comprehensive experimental program was designed and implemented. The design experimental program is shown in figure (1). The figure shows that the design program consists of two divisions. The first division is office work, whereas the second stage is lab work. The office work was designed to begin with reviewing of previous studies related the grouting of asphalt concrete mixes all over the world. The reviewing included the advantages, disadvantages, limitations, etc. after that the research material were selected. The selection takes into consideration the normal condition of the surface layer asphalt mixtures as well as the condition of Egypt related to the costs of grouting materials. The investigated mixes composed of limestone as coarse aggregate, sand as fine aggregate, lime stone dust as mineral filler and 60/70 penetration grade asphalt cement. This is the typical materials used for road construction in Egypt. Table (1) presents the gradation of coarse aggregate, sand, and mineral filler. The selected grouting materials are OPC, fine sand and cement dust (CD). The gradation and bulk specific gravity of OPC, fine sand, and CD are shown in Table (2). Fly ash, plasticizer and silica fume were not selected to investigate because of their high cost. After that, four open gradations were selected to investigate the efficiency of their grouting. Dense mix gradation was selected as a control mix for comparison. Both open and dense gradations are shown in Table (3). To evaluate different technique of grouting three grouting techniques were investigated. The first technique is grouting with OPC only. The second technique is grouting with OPC and fine sand. Three percentages of OPC and sand by weight were investigated. These percentages were: (a) 75% OPC and 25% fine sand, (b) 50% OPC and 50% fine sand, and (c) 25% OPC and 75% fine sand. The third technique is grouting with OPC and CD. Three percentages based on mix weight of OPC and CD was investigated. These percentages were: (a) 75% OPC and 25% CD, (b) 50% OPC and 50% CD, and (c) 25% OPC and 75% CD. Based on the results of preliminary experimental stage explained in this second division of the experimental program, the more suitable grouting materials were selected. Also, the more efficient open graded mix was chosen. After that four different compaction efforts were investigated to define the more suitable compaction effort for mix grouting. The last stage of office work was the analysis of the results of experimental work.

The laboratory work is the second division of experimental program. It begins with the qualification tests on the selected material. The qualification tests are: (a) los angles abrasion test, (b) absorption, disintegration, and specific gravities test, and (c) characteristics of asphalt cement. Table (4) illustrate the physical properties of the used coarse aggregate. The table shows that all properties of coarse aggregate are within Egyptian specification [13]. While the characteristics of asphalt cement are shown in Table (5). The second stage of the laboratory work division is the preliminary laboratory works. It concludes: (a) carrying out Marshall test, unconfined compression test, and indirect compression test for dense asphalt mix, (b) implementing permeability test, calculation of the theoretical asphalt content (AC), and voids in total mix for porous asphalt mix, and (c) conducting water cement ratio test, unconfined compression test, and indirect tensile test for grout mixes. The compaction effort applied for testing dense mix was 75 blows/side (corresponding to heavy traffic condition). While the compaction effort for porous mix was 50 blows/side (corresponding to medium traffic condition). The first objective of the preliminary laboratory work stage is defining optimum asphalt content, Marshall Properties, compression strength, and tensile strength of dense mix. While the second objective is the measuring of permeability using constant head permeameter as shown in Figure (2), calculation of theoretical AC, and determination of voids in total mix. The third objective is determination of water cement ratio using marsh funnel. The acceptance criterion for the grout viscosity within range of 7.0 to 9.0 seconds [11], measured immediately after mixing. For comparison, water has a Marsh flow cone viscosity of 6.0 seconds. Figure (3) shows marsh flow cone dimensions. Also, measuring of compression and tensile strengths are considered within the third objectives of preliminary work. The preliminary work is followed by the main laboratory work stage. The main laboratory work stage consists of two sub-stages. The first one is preparing the study porous mixes using the selected gradation and for different compaction efforts (0, 15, 35, and 50 blows/side). This is followed by grouting the compacted porous asphalt mixes using the selected grouting techniques. The objectives of the main laboratory work are investigating the effect of compaction efforts on the characteristics of grouted mixes as well as the efficiency of grouting technique.

Finally the results of this study are collected and analyzed. The conclusions and recommendations of the research were deduced. The last division of this work is the writing of paper.

3. Results and Discussion

Research results will be discussed in this section under two titles. The first will be about preliminary work. Based on the discussing of the preliminary work results, the mix used to study the effect of different grouting conditions will be selected. Also, the investigated grouting material type will be chosen. In the second title, the characteristics of grouted asphalt mixes under different conditions will be evaluated.

3.1. Preliminary Work Results.

3.1.1 Selection of the More Suitable Porous Asphalt Mix for Grouting

Thoroughly discussing of the results of preliminary work will be conducted to select the more suitable porous asphalt mix for grouting. Table (6) shows the asphalt content (AC) required for producing porous mixes based on its gradation mentioned in Table (3). The AC was determined using the Equation (1) [14].

$$AC = 3.25(\propto)\Sigma^{0.2} \qquad \text{Eq. (1)}$$

Where

$\propto = 2.65/SG_{agg}$, Σ = Specific surface area $= 0.21C + 5.4S + 7.2s + 135f$, $\mathbf{SG_{agg}}$= Apparent specific gravity of aggregate blend, **C**= Percentage of material retained on 4.75mm sieve, **S**= Percentage of material passing 4.75mm sieve and retained on 600μm sieve, **s**= Percentage of material passing 600μm sieve and retained on 75μm sieve, **f**= Percentage of material passing 75μm sieve.

Then, porous asphalt mixes of materials and gradations shown in Tables (3), (4), and (5) were prepared using the theoretical AC. The properties of these mixes related to their ability for grouting were determined and presented in Table (7). The table illustrates the hydraulic connectivity coefficient (K), porosity, and voids in total mix (VTM) as determined from Equation (2) [11].

$$VTM = \left(1 - \frac{w_{air}}{v \times SG_T}\right) \times 100 \qquad \text{Eq. (2)}$$

Where

VTM = Voids in total mix, $\mathbf{W_{air}}$ = Dry weight of specimen, **v**= Volume = $\frac{\pi D^2 H}{4}$, $\mathbf{SG_T}$= Theoretical Specific gravity.

The bulk and apparent specific gravities and drain down for the investigated porous mixes were also shown in Table (7).

Analyzing the AC's of the investigated mixes shows that their minimum value is 4.4% achieved for mix OGM_4, whereas the maximum value is 4.6% achieved for mix OGM_1. This means that the variation is about 4% {(4.6-4.4)/4.6)}. This variation can be considered as insignificant difference. All mixes have acceptable drain down values (max = 0.3%) according to AASHTO specification (T305). The hydraulic connectivity (K) of the investigated porous mixes was analyzed using its values presented in Table (7). The table shows that the mix OMG_4 achieves the highest K which ranging between one time and three quarter to two times and one quarter of OGM_2 and OGM_3, respectively. In spite of VTM of OGM_4 is slightly more than that of OGM_3 (the difference is about 4%), the K value of OGM_4 is about twice of that of OGM_3. This may be due to the absence of sand (fine aggregate) in OGM_4 which leads to increasing the connectivity between the voids of the mix. It can be deduced also that the porous asphalt mix OGM_4 is the more suitable mix for grouting. Hence, OGM_4 will be selected to complete the research and investigate the grouting conditions.

To evaluate the characteristics of the grouted mixes under different conditions, reference mix composed of lime stone course aggregate, fine aggregate, mineral filler and 60/70 asphalt cement was designed using Marshall procedure. The AC as well as Marshall characteristics of this mix are presented in Table (8). Both unconfined compression and indirect tensile tests were carried out also for the reference mix. Table (8) illustrates also unconfined compression and indirect tensile strengths.

3.1.2 Selection of the More Suitable Grout Materials for Grouting

Seven Grout types were tested to select the more suitable for grouting. The seven types were 100% OPC (G1), 75% OPC with 25% CD (G2), 50% OPC with 50% CD (G3), 25% OPC with 75% CD (G4), 75% OPC with 25% fine sand (G5), 50% OPC with 50% fine sand (G6) and 25% OPC with 75% fine sand (G7). The required water content to achieve the allowable grout flow value was get using Marsh funnel and presented in Table (9). The table also presents the marsh flow value, grout liquid density and specific gravities and absorption for the solid grout. The compression and tensile strengths for cubic samples of 5×5×5 cm and cylindrical samples of 5 cm diameter and 10 cm height the were determined at 7 and 28 days curing periods and presented in Table (10).

Table (9) illustrates the percentages of water required for liquefying different grout materials. The table shows that it ranges between 0.24 and 0.51. The minimum value was achieved for G7, whereas the maximum value was achieved for G4. This may be due to the increasing of fine sand for the minimum value and the increasing of cement dust for the maximum value. It can be concluded that using cement dust leads to increase water content and decrease density. While the using of fine sand reduces the required water content and increases the density. The value of water content will not be a factor in the selection of the suitable grout types. It is only used to produce a liquid grout has an ability to penetrate and fill the porous asphalt mix voids. The selection of the more suitable grout material will be based on the compression and tensile characteristics as well as its price. Compression and tensile strengths for tested grout materials at 7 and 28 days of curing are presented in Table (10). It shows that the grout material G1 has the highest values in both compression and tensile strengths after 7 days of curing. These values are 3525 and 404 psi, respectively. The grout material G5 has the highest values after 28 days of curing; 4502 psi compression and 350 psi tensile strength. On the other hand, the grout material G4 has the lowest compression and tensile strength values. The results show that the grout materials composed of fine sand and cement achieved higher compression and tensile strengths compared with the identical grout materials containing cement dust instead of fine sand. Fine sand and cement dust have approximately the same cost. So, using cement dust in grouting is not preferred when compared with fine sand. This means that the grout materials G2, G3 and G4 will be neglected in the grout material selection. Based on these results three grout types are selected for porous asphalt mix grouting. The first selected grout material is G1 because of the higher values of the strengths for the early curing period (7 days). The second selected grout material is G6 due to its low price compared with G1. The last chosen grout material is G7. It was selected to examine lowest price material.

3.2Contribution of Compaction Effort on Permeability and Strength of Investigated Porous Mixes.

The contribution of compaction efforts on both volumetric and strength characteristics of the most suitable groutable mix (OMG4) are presented in Table (11) and (12). The table illustrates that the highest K and VTM values (2.14 cm/sec and 38.1%) were achieved for zero compaction specimens. Slightly compaction effort (15 blows) causes drastically decreasing of these values. It produced mix of about half K value and 83% VTM compared with those of zero compaction specimens. This may be due to the gap gradation of OMG4. This explained by the absence of fine aggregate sizes from the specimens. The absence of fine aggregate sizes from OMG4 specimens may also explain the drastically decreasing resulted from slightly compaction effort. The redistribution of coarse aggregate particles will occur quickly due to the high voids in the gap gradation mix. Increasing the compaction effort higher than 15 blows/side until 75 blows caused slightly and gradual changing in both K and VTM values. The minimum values of 0.48 cm/sec and 26.5% are achieved for K and VTM at compaction effort 75 blows/side. This can be explained by two reasons. The first is the drastically decreasing of specimen voids occurred due to the slight compaction (15 blows) as explained previously. The second is the probability of specimen particles crushing happened because of the presence of only course aggregate and mineral filler and the absence of fine aggregate. This may lead to the exposing of coarse aggregate to the effect of hammering during specimen compaction. The table also shows similar trace for bulk specific gravity like that achieved for both K and VTM traces. This can be due to the same explanation mentioned before.

Compaction effort did not contribute in the percent of asphalt content required to mix any of investigated porous mixes. That is due to the base of calculating procedure. Theoretical equation was used in determining the asphalt content percent required for each porous mix as well as that for reference mix. The determining of asphalt amount required for mixing one cubic meter of asphalt mix was based on the measured bulk specific gravity for the design mixes as well as the calculated percent of asphalt content.

Compression and tensile strengths as well as Marshall stability of porous mixes are highly affected by compaction effort and testing temperature. Zero compression strength and stability are recorded for zero compacted specimens at 60^o c temperature. The uncompact specimens gain its compression strength only from the bond between asphalt binder and coarse aggregate. At 60^o c the asphalt cement loses its adhesive ability, so unstable mix will be resulted. It is noted that for the compaction efforts from 15 to 50 blows/side, the mixes strengths increase as well as the compaction effort increase. Otherwise, increasing the compaction effort to 75 blows inversely affects Marshall Stability and ITS. This may be due to the change in aggregate gradation caused by crushing of coarse aggregate particles as shown Table (13). The table shows that the increasing of compaction effort applied to the open graded (No fine aggregate) asphalt to 75 blows /side creates about 20% fine aggregate. This presence of fine aggregate may be caused by hammering effect and the absence of ample space for aggregate movement which prevent the aggregate to reorient. Generally, dense asphalt mixes have strength greater than the porous asphalt mixes. This may be due to the low air voids resulting from both of well graded aggregate and mechanical compaction.

Although, the theoretical calculated asphalt content percent of the five investigated porous asphalt mixes are the same at any compaction effort; the asphalt amount required for one cubic meter of asphalt mixture increases. This mean that the amount of both aggregate and asphalt required for the same volume are the increasing with the increasing of compaction efforts. This leads to increasing the bulk specific gravity of the resulted porous asphalt mixes. Consequently, enhancing the compression and tension characteristics of the resulted porous asphalt mixes.

Compacting porous specimen by 75 blows leaded to its coarse aggregate degradation. This is the main reason of decreasing VTM to its minimum value (26.5%). Consequently, the specimen permeability (K) reached to its minimum value (0.48 cm/sec). This value doesn't enable from effective grouting. The changing of the original aggregate sizes may be the main reason of decreasing the resistance of the resulted mix to both compression and tension strengths. So, discarding the condition of 75 blows compaction efforts is considered preferable form the study plan.

3.3 Contribution of Grouting Material on Strength of Grouted Asphalt Mixture

Compression strength, tension strength and stability analysis are conducted in this section to three main groups of specimens. The first one is the OMG_4 specimens compacted at 0, 15, 35 and 50 blows/side and grouted by OPC. This group is coded by GAM1. The second one is the OMG_4 specimens compacted at 0, 15, 35 and 50 blows/side and grouted by 50%OPC with 50% fine sand. This group is coded by GAM2. While the third group is OMG_4 specimens compacted at 0 and 50 blows/side and grouted by 25% OPC with 75% fine sand. This group is coded by GAM3. All investigated samples achieve percent of grouting exceeds 95% of the grouted porous asphalt mix air voids. Only 50% of the air voids of the mix GAM3 at 50 blows compaction efforts hardly achieved. Figure (4) shows saw cut in the grouted asphalt mixes at different compaction efforts. The figure also illustrates the full distribution of the grout material between the coarse aggregate particles of the porous asphalt content.

The analyses are included the following:

a. Unconfined Compression strength of grouted asphalt mixtures
b. Marshall stability of grouted asphalt mixtures
c. Indirect Tensile strength of grouted asphalt mixtures

a. Compression strength of grouted asphalt mixtures.

Figure (5) and (6) show the compression strength after 7 and 28 days of curing for OMG4 grouted using different types of grout at different compaction efforts. Analyzing the results, it can be noticed that grouting of OGM_4 porous mixes by G1 and G6 achieved positive, significant, and noticeable effect on their compression strength after 7 and 28 days. The improving compression strength after 7 days reaches about three times of the corresponding of traditional mixes ordinary used in surface asphalt layers. The figure shows that the compression strength of the mix GAM1 ranges between 552 and 487 psi after 7 days. This variation was between 565 and 542 psi after 28 curing days. The figure also shows that the highest compression strength value for the mix GAM2 (441 psi) is achieved for the specimen compacted by 35 blows; whereas the lowest value (385 psi) was achieved for the specimen compacted by 50 blows. About 90% of 28 days compression strength was achieved after 7 days of curing. The variation in compression strength after 7 and 28 days for OMG4 grouted by G1 and

G6 is insignificant and random. It did not depend on the compaction effort. The high compression strength recorded for the grouted mixes GAM1 and GAM2 can be due to the replacement of low strength asphalt paste (asphalt cement, sand and mineral filler) in traditional mix by high strength cement paste (OPC or OPC mixed with sand) grouted in the voids in porous asphalt. This leads to fully interlock between coarse aggregate and the grout which generates high friction between the grouted mix particles. On the other hand, uncompact GAM3 has compression strength of about one time and quarter of traditional mix. This means that the grout material G7 approximately have the same effect on compression strength as well as asphalt paste. Whereas, GAM3 at compaction effort of 50 blows has compression strength less than that of reference mix by about 21%.

A comparison between grouting OMG4 using both G1 (100% OPC) and G6 (50% OPC+50% fine sand) can be conducted. The grouted mix GAM1 has compression strength higher than that of GAM2 by about 17% after 28 days. That is to say using 50% additional cement in grouting the investigated mix OMG4 caused small increasing the compression strength. So, the using of grouting material of 50% OPC with 50% fine sand (G6) is highly recommended.

b. Marshall stability of grouted asphalt mixture.

Figure (7) and (8) show the Marshall stability after 7 and 28 days of curing for OMG4 grouted using different types of grout at different compaction efforts. Figures show that grouting of OGM_4 porous mixes by G1 and G6 grout achieved positive, significant, and noticeable effect on their stability after 7 and 28 days. The enhancing of stability after 7 days reaches about three times of the corresponding of traditional mixes. The figure shows that the Marshall stability of the mix GAM1 ranges between 8499 ib at 0 compaction effort and 6126 ib at 50 blows after 7 days. This variation was between 9009 ib and 6861 ib after 28 curing days at the same compaction efforts. The figure also shows that the highest 7 days stability value for the mix GAM2 (7066 ib) is achieved for the specimen compacted by 0 blows; whereas the lowest value (5354 ib) was achieved for the specimen compacted by 50 blows. About 92% of 28 days compression strength was achieved after 7 days of curing for mix GAM1 and 89% for mix GAM2. The stability values after 7 and 28 days for OMG4 grouted by G1 and G6 are inversely affected by compaction efforts. The high stability values recorded for the grouted mixes GAM1 and GAM2 can be due to the replacement of low strength asphalt paste (asphalt cement, sand and mineral filler) in traditional mix by high strength cement paste (OPC or OPC mixed with sand) grouted in the voids in porous asphalt. This leads to fully interlock between coarse aggregate and the grout which generates high friction between the grouted mix particles. On the other hand, uncompact GAM3 has stability value of about one time and half of traditional mix. Whereas, GAM3 at compaction effort of 50 blows has stability less than that of reference mix by about 28%.

A comparison between grouting OMG4 using both G1 (100% OPC) and G6 (50% OPC+50% fine sand) can be conducted. The grouted mix GAM1 has compression strength higher than that of GAM2 by about 11% after 28 days. This means that using 50% additional cement in grouting the investigated mix OMG4 caused small increasing in the mix stability. So, the using of grouting material of 50% OPC with 50% fine sand (G6) is highly recommended.

c. Indirect tensile strength of grouted asphalt mixture.

Figure (9) and (10) show the indirect tensile strength after 7 and 28 days of curing for OMG4 grouted using different types of grout at different compaction efforts. Analyzing the results, it can be noticed that grouting of OGM_4 porous mixes by G1 and G6 achieved positive, significant, and noticeable effect on their tensile strength after 7 and 28 days. Corresponding of traditional mixes the increasing of tensile strength after 7 days are 16 and 28% for GAM1 and GAM2, respectively. This increasing reaches 22 and 65% for 28 days of curing. The figure shows that the tensile strength of the mix GAM1 ranges between 93 and 109 psi after 7 days. This variation was between 95 and 119 psi after 28 curing days. The figure also shows that the highest tensile strength values were recorded for the mix GAM2 at 228 days of curing. These values range between 134 psi achieved for the specimen compacted by 15 blows and 149 psi achieved for the specimen compacted by 50 blows. About 95 % of 28 days compression strength was achieved after 7 days of curing for the mix GAM1. While, 77% recorded for the mix GAM2. The tensile strength after 7 and 28 days for OMG4 grouted by G1 inversely affected by compaction effort. Whereas that grouted by G6 is proportionally affected by compaction efforts. The high tensile strength achieved for the grouted mixes GAM2 over GAM2 can be due to that the grout G6 coarser than G1. This leads to a high friction between the grouted mix particles. Also, the reason of increasing the tensile strength for the mix GAM2 with the increasing compaction efforts can be explained by the increasing of surface area covered

With asphalt. On the other hand, the mix GAM3 has compression strength lower than that of traditional mix by about 15%. So, the using of grouting material of 50% OPC with 50% fine sand (G6) is highly recommended.

Over viewing the grouted mixes test results, the mix GAM2 at compaction efforts 35 blows/side can be considered as the optimum mix. This is due to its high value of tensile strength as well as compression strength and stability. Using this mix saves about 36.24% of asphalt content compared of that used for reference dense mix. Increasing of compression and stability by three times and 67% increasing in tensile strength was achieved for this mix.

4. Conclusions & Recommendations

Analyzing the study results, it can be concluded that:

- Grouting technique shows high and positive efficiency in increasing each of compression and tensile strength as well as stability of high permeable asphalt mixes to values higher than that of identical of traditional dense asphalt mixes
- Grouting technique has proved efficiency in decreasing the asphalt quantity required for high permeable asphalt mixes than that of identical of traditional dense asphalt mixes
- The more suitable grouting material for high permeable mixes are ordinary portland cement (OPC) as well as mixture of 1:1 OPC and silica sand
- Compaction efforts show small effect on the characteristics of grouted high permeable mixes.
- The optimum conditions of producing the best grouted high permeable mixes are achieved for the mix compacted at 35 blows/side and grouted using grout mixture of 1:1 OPC and silica sand.
  This mix saves about 36.24% of asphalt content compared of that used for reference dense mix and increasing of compression and stability by three times and 67%, increasing in tensile strength.
- Cement dust is not recommended as a grout filler material when compared by the fine silica sand.
- The grouted mixtures using 100% OPC and 50% OPC with 50% sand achieve compression strength values ranging between 250% and 370% higher than the corresponding of traditional mix.
- The grouted mixtures using 100% OPC and 50% OPC with 50% sand achieve higher stability values with range of

270% to 420%. Higher than the corresponding of traditional mix.

- A field test samples is strongly needed to study the performance of the grouted mixes included in this study.

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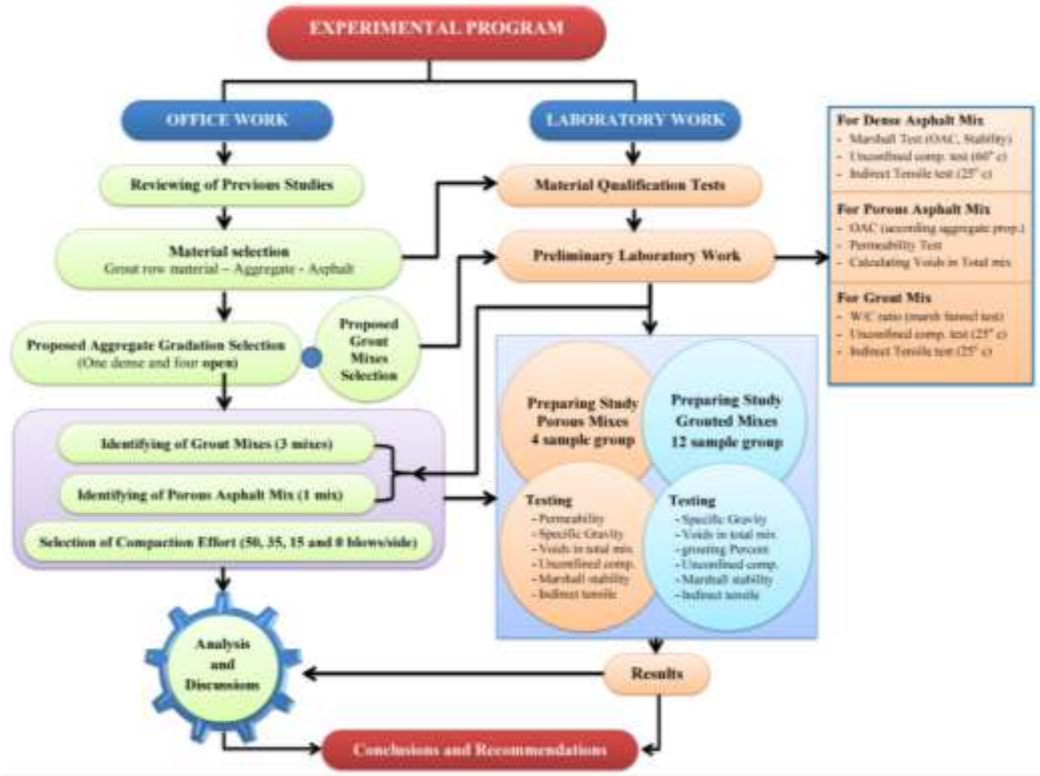


Figure (1): Experimental Program Diagram

Table (1): Gradation of Investigated Aggregate.

Sieve size	Coarse Aggregate		Fine aggregate	Mineral filler
	20 mm	10 mm		
1"	100			
3/4"	81.9			
1/2"	14.0	100		
3/8"	2.30	91.2	100	
No.4	0.00	17.5	97.9	
No.8		0.51	54	
No.30		0.46	30	100
No.50		0.45	18	98
No.100		0.43	4	94
No.200		0.40	54	82

Table (2): Characteristics of Grout Materials

		OPC	Fine Sand	Cement Dust
Gradation, % passing	No. 40	100	100	100
	No. 60	100	99	100
	No. 100	100	2.9	100
	No. 200	100	0.3	91
Bulk SG		3.15	2.66	2.84

Table (3): Gradations of Reference Dense Mix as well as Investigated Mixes

Sieve Size	Dense Gradation (4C), % passing	Open Gradations, % passing			
		OG_1	OG_2	OG_3	OG_4
1"	100	100	100	100	100
3/4"	90	100	100	100	100
1/2"	80	90	90	100	100
3/8"	70	35	38	90	90
No.4	55	15	8	10	3
No.8	40	5	5	5	3
No.30	25	-	-	-	-
No.50	15	-	-	-	-
No.100	10	-	-	-	-
No.200	5	3	3	3	3

Table (4): Physical Properties of Coarse Aggregate Used in Reference Dense Mix as Well as Investigated Mixes

Test Name	Designation Code	Egyptian Specification [13]	Test Result	
			20 mm N.S	10 mm N.S
Los Angeles Abrasion	AASHTO (T96)	≤ 40%	29.1	28.6
Water absorption	AASHTO (T85)	≤ 5%	2.09	1.17
Apparent specific gravity	AASHTO (T85)	-	2.60	2.60
Flat or Elongated Particles	ASTM (D4791)	≤ 10%	1.3	1

Table (5): Characteristics of Asphalt Used in Manufacturing Investigated Mixes

Test	Results of Asphalt 60/70	Specification Limits
Penetration of Asphalt at 25° C, 0.01mm	64	60-70
Kinematics Viscosity at 135°C, Cst.	334	≥ 320
Specific bulk density	1.02	-

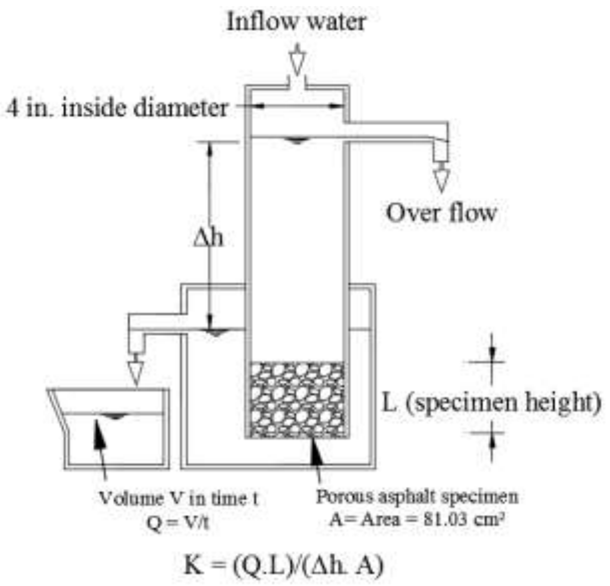


Figure (2): Constant Head Permeameter Used in Measuring the Hydraulic Connectivity of Investigated Porous Mixes

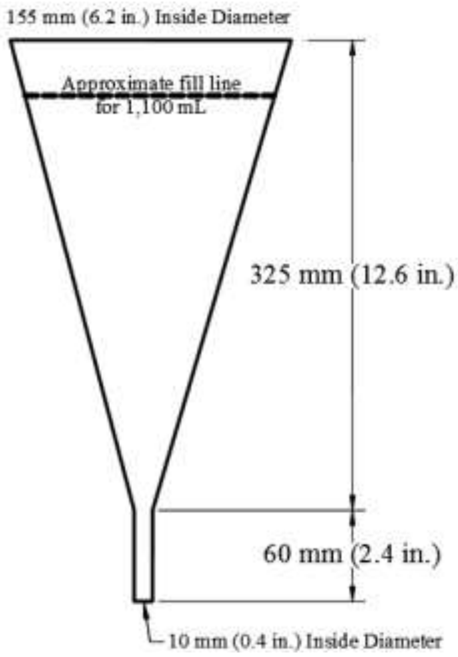


Figure (3): Marsh Flow Cone (Marsh Funnel) Used in Measuring Grout Flow

Table (6): Theoretical Asphalt Content of Porous Asphalt Mixtures

Gradation	App. SG	∝	∑	AC, %
OG_1	2.59	1.025	4.88	4.6
OG_2	2.58	1.026	4.51	4.5
OG_3	2.6	1.020	4.62	4.5
OG_4	2.6	1.021	4.25	4.4

Table (7): Properties of Porous Asphalt Mixtures.

Mix code	Bulk S.G.	App. S.G.	K cm/sec	VTM %	Porosity%	Drain down [AASHTO T305] , %
OGM_1	1.86	2.30	0.33	23.6	19.3	0.25
OGM_2	1.85	2.28	0.38	23.7	18.7	0.25
OGM_3	1.78	2.32	0.31	26.6	23	0.27
OGM_4	1.75	2.30	0.67	27.7	24.6	0.28

Table (8): Marshall Test Results for Reference Asphalt Mixture

Property	Value	Egyptian spec., [13]
Opt. asphalt content (OAC), %	5.20	-
Marshall stability, ib	2147	1987 (900 kg)
Unit weight, t/m^3	2.30	-
Marshall flow, 0.01 inch	13.10	8 - 16
Air voids, %	3.40	3 - 5
Voids in mineral aggregate (VMA), %	14.50	15
Unconfined Compression strength (UCS), psi	165	-
Indirect Tensile Strength (ITS), psi	85	-

Table (9): Different Characteristics of Grout Materials

code	composition (by weight)				grout properties		Solid sample SG		
	cement	sand	cement dust	water	liquid density, gm/cm^3	marsh flow, sec.	Bulk	App.	Absorption %
G1	0.67	0	0	0.33	1.79	8.5	1.80	1.94	3.91
G2	0.46	0	0.15	0.39	1.64	8.8	1.62	1.74	4.36
G3	0.27	0	0.27	0.46	1.54	9.0	1.51	1.59	3.12
G4	0.12	0	0.37	0.51	1.43	8.4	1.43	1.47	2.08
G5	0.52	0.17	0	0.31	1.82	8.4	1.79	1.94	4.15
G6	0.37	0.37	0	0.26	1.92	8.9	1.88	1.99	2.86
G7	0.19	0.57	0	0.24	1.89	8.5	1.93	2.00	1.73

Table (10): Mechanical Properties for Grout Mixes

code	UCS, psi		ITS, psi	
	7 day	28 day	7 day	28 day
G1	3525	4379	404	fail due to shrinkage
G2	1429	2308	154	172
G3	305	436	67	79
G4	100	238	14	32
G5	2860	4502	167	350
G6	1973	2670	151	236
G7	489	1126	51	105

Table (11): Volumetric Properties of Porous Asphalt Mixtures at Different Level of Compaction Compared with the Reference Dense Mix

Asphalt amount*, kg/m^3	**%Asphalt content (%AC)**	**SG_{Bulk}**	**VTM, %**	**K, cm/sec**	**Compaction effort, blows/side**	**Asphalt mixture type**
63.6	4.40	1.51	38.1	2.14	0 (Uncompact)	Porous (**OGM_4**)
70.0	4.40	1.66	31.7	1.10	15	
72.5	4.40	1.72	29.4	0.76	35	
73.8	4.40	1.75	27.7	0.67	50	
75.4	4.40	1.79	26.5	0.48	75	
113.7	5.20	2.30	03.4	0.00	75	Dense

*$Asphalt\ amount = \frac{SG_{Bulk} \times (\%AC)}{(100+\%AC)} \times 1000 \quad , kg/m^3$

Table (12): Effect of Compaction Effort on the Strength of Porous Asphalt Mixtures

ITS, (psi)	**Stability, ib**	**UCS, (psi)**		**Asphalt amount, kg/m^3**	**%Asphalt content (%AC)**	**Compaction effort, blows/side**	**Asphalt mixture type**
25^o C	60^o C	60^o C	25^o C				
14	0	0	78	63.6	4.40	0	Porous (**OGM_4**)
28.5	243	19	149	70.0	4.40	15	
37.5	534	29	199	72.5	4.40	35	
55.5	971	39	280	73.8	4.40	50	
27.4	558	54	176	75.4	4.40	75	
85	2147	165	-	113.7	5.20	75	Dense

Table (13): Gradation of porous asphalt mixes after compaction, % passing

Sieve Size	Compaction effort, blows/side		
	Zero	50	75
1/2"	100	100	100
3/8"	90	92.62	93.13
No.4	3	15.74	24.30
No.8	3	5.31	9.42
No.50	3	3.20	4.21
No.100	3	3.19	4.14
No.200	3	3.15	4.11

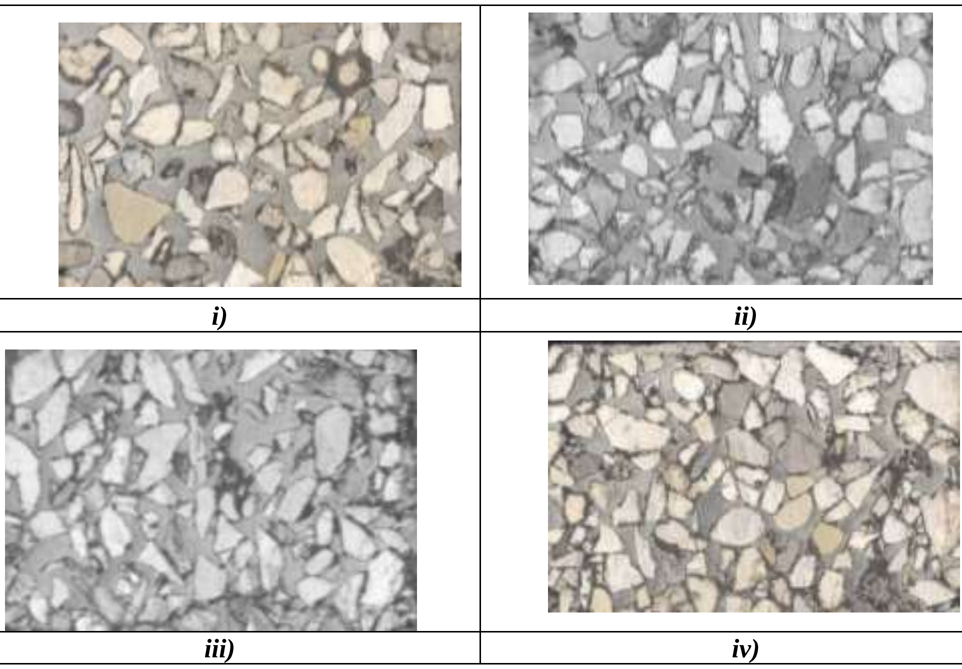


Figure (4): Saw Cut in Grouted Asphalt Mixes at Different Compaction Efforts, i) 0 blows/side, ii) 15 blows/side, iii) 35 blows/side and, iv) 50 blows/side

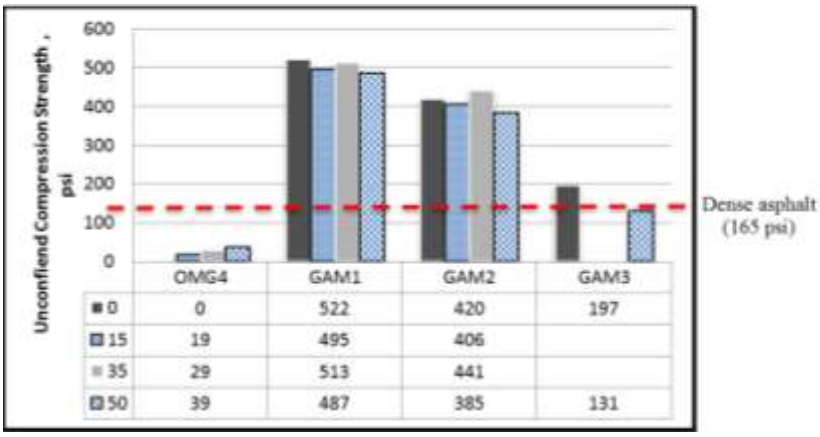
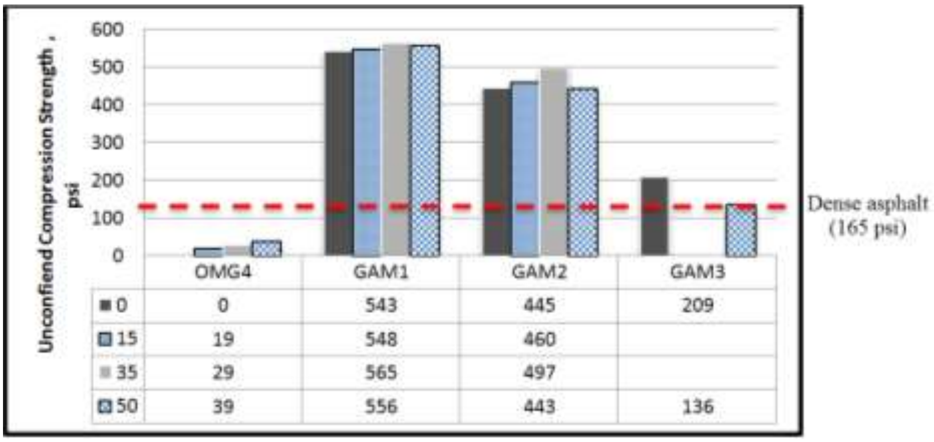
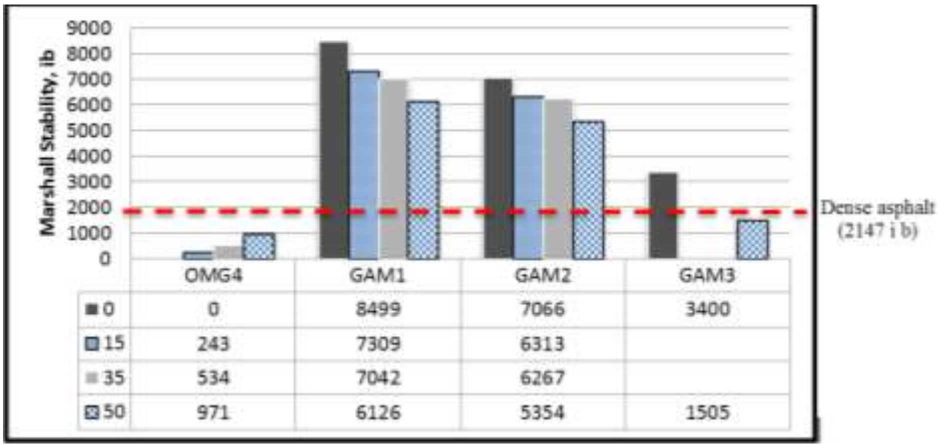


Figure (5): Unconfined Compression Strength Results (7 days curing at 60°c test temp.)



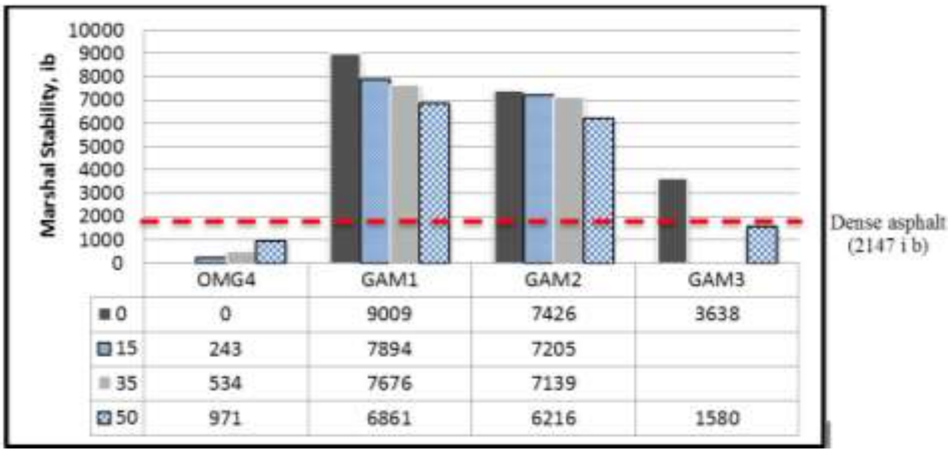
	OMG4	GAM1	GAM2	GAM3
0	0	543	445	209
15	19	548	460	
35	29	565	497	
50	39	556	443	136

Figure (6): Unconfined Compression Strength Results (28 days curing at 60^{o}c test temp.)



	OMG4	GAM1	GAM2	GAM3
0	0	8499	7066	3400
15	243	7309	6313	
35	534	7042	6267	
50	971	6126	5354	1505

Figure (7): Marshall Stability Results (7 days curing at 60^{o}c test temp.)



	OMG4	GAM1	GAM2	GAM3
0	0	9009	7426	3638
15	243	7894	7205	
35	534	7676	7139	
50	971	6861	6216	1580

Figure (8): Marshall Stability Results (28 days curing at 60^{o}c test temp.)

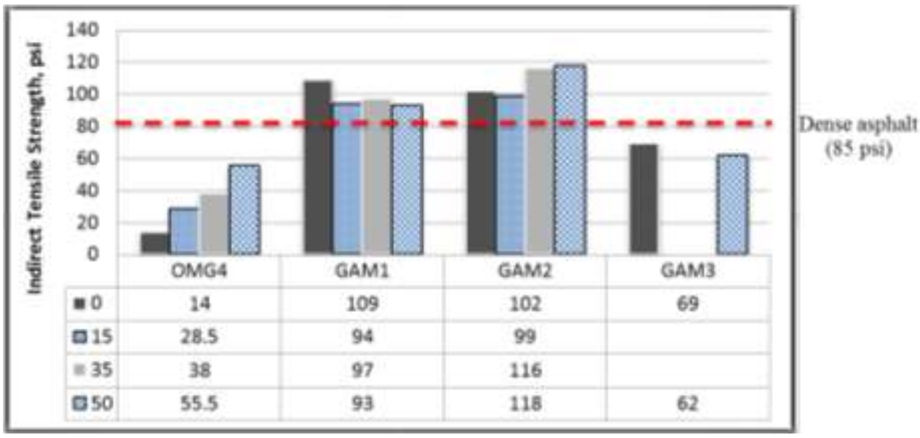


Figure (9): Indirect Tensile S strength Results (7 days curing at 25ºc test temp)

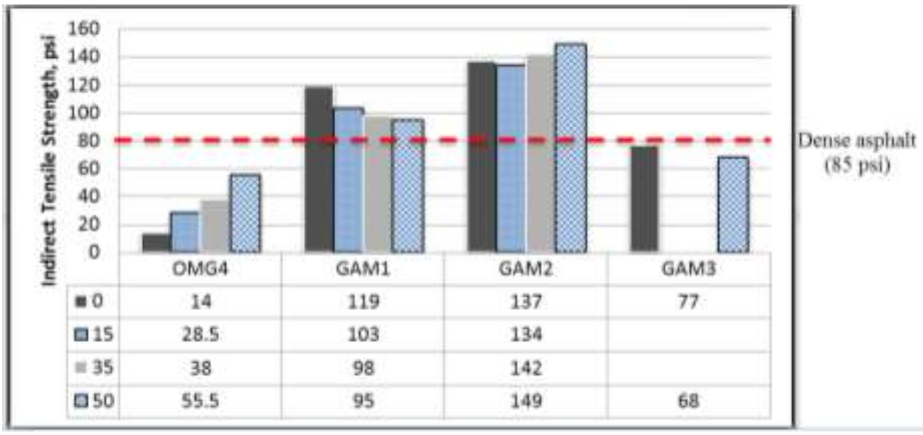


Figure (10): Indirect Tensile Strength Results (28 days curing at 25ºc test temp)