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Evaluation of steel slag and crushed limestone mixtures as subbase material in flexible pavement

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KEYWORDS
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Strain

Abstract Steel slag is produced as a by-product during the oxidation of steel pellets in an electric arc furnace. This by-product that mainly consists of calcium carbonate is broken down to smaller sizes to be used as aggregates in pavement layers. They are particularly useful in areas where a good-quality aggregate is scarce. This research study was conducted to evaluate the effect of quantity of steel slag on the mechanical properties of blended mixes with crushed limestone aggregates, which used as subbase material in Egypt. Moreover, a theoretical analysis was employed to estimate the resistance for failure factors such as vertical deformations, vertical and radial stresses and vertical strains of subbase under overweight trucks loads. These loads cause severe deterioration to the pavement and thus reduce its life. The results indicated that the mechanical characteristics, and the resistance factors were improved by adding steel slag to the crushed limestone.

1. Introduction

Chang in modern traffic characteristics has led to higher vehicle loads, tire pressures and traffic volumes. Current research illustrates that truck weights over 113.4 ton (250,000 lb) and tire pressures of 150 psi have been frequently reported. These changes represent a serious challenge to the pavement layers as they have caused predatory occurrence of distresses, permanent deformation/rutting and fatigue failure [1]. This deformation causes map cracking, chuck holes, settlement and undulations similar to those observed in some Egyptian roads. Certainly, accumulation of these deformations reduces the pavement life, increases the maintenance costs and may cause a complete failure of the pavement. Increasing the resistance of flexible pavement layers, against permanent deformation, definitely, will increase pavement life, decrease maintenance cost as well as prevent the early reconstruction. Researches on the available aggregates have shown that there is a general scarcity of good-quality aggregates since most of the available limestone aggregates are friable carbonates of sedimentary origin. These aggregates have been low crushing strength, low resistance to weathering, and low resistance to traffic abrasion.

Abbreviations: CBR, California bearing ratio; FE, finite element; OMC, optimum moisture content; MDD, maximum dry density; MR, resilient modulus; SSP, steel slag percentage

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Thus, they are unsuitable for use in areas where a high skid resistance is required (e.g. roundabouts, slopes, wet surfaces and intersections) [2].

Steel slag is a by-product formed during the steel manufacturing process. It is a non-metallic ceramic material formed from the reaction of flux such as calcium oxide with the inorganic non-metallic components present in the steel scrap. The use of steel slag reduces the need of natural rock as constructional material, hence preserving our natural rock resources and reducing the need for dumping ground. Screening of the steel slag will be done to ensure the aggregate is suitable for use as construction material. Since 1993, steel slag aggregates have been used commercially in the region for road surfacing [3].

Steel slag contains significantly higher calcium oxide and iron oxide compared to granite rock. Granite rock contains high silica and alumina content and is generally hydrophilic. The good resistance to stripping by the steel slag aggregates indicates that the material is more superior to natural granite as road surfacing material. The superior adhesion of the steel slag with bitumen would also minimize potential moisture damage of the steel slag mix. The formulation of the road mixes using steel slag as aggregates has shown to give better rut resistance and mechanical stability, which indicates a more lasting wearing course for the road [4].

Researches regarding recycling and utilization of steel slag in different fields have been carried out in recent years. It was used as mineral additive for cement-based materials to improve mechanical properties of concrete. Some studies used steel slag to produce Portland cement with iron slag and limestone, and confirmed that the compressive strength of concrete was above standard values. Other researches studied the characteristics of bricks made from steel slag and revealed that it reduced the required firing temperature. Steel slag could also be used to remove some hazardous substances such as ionic copper and ionic lead from waste water. In many researches, steel slag was used as aggregate in concrete. Researches have confirmed that the durability of concrete with steel slag was improved, and the compressive strength and split tensile strength were much higher than that with limestone. However, few reports were found about utilization of steel slag as aggregate in asphalt mixture [5].

Although there are advantages in each application, the use of steel slag as a granular material is a promising area due to the following reasons [6]:

(i) Larger quantities of steel slag can be used as a granular material, compared with another usage.
(ii) The process for granular use is technically sound, simpler and well developed.
(iii) There are fewer concerns on long-term stability in unbound conditions, highway granular base and subbase, for instance.
(iv) Volume expansion test method has also been developed.
(v) The steel slag industry has maturely placed their production and marketing emphasis on granular materials for unconfined utilizations.

Steel slag treating and processing technology has been well developed for the last couple of decades which have made it possible for steel slag to be used as granular base or subbase materials in large scales. However, the fact is that steel slag aggregate has not been extensively used in construction, especially its use as a granular material. The main reason for the low scale utilization is the lack of quantified criteria to guide the appropriate use for a special steel slag in a special use. It is imperative to establish different criteria for different utilizations of steel slag [6]. Accordingly, Adding steel slag to the limestone aggregates may cause an improvement to the bearing capacity and frost action of granular soil.

For all above reasons, this work intended to explore the feasibility of steel slag aggregates for subbase mixture, and compare it with limestone aggregate. This study was conducted to ascertain the mechanical properties and failure factors characteristics of subbase layer prepared with steel slag and limestone aggregates.

2. Problem statement and study objective

During the last few years excessive damages were observed on several highways, mostly on high volume major roads. The reasons behind can be observed: layers strength and thickness, mixture design, change in traffic load, etc. In Egypt, there are many types of heavy vehicles of 6-axles of total weight ranging over from 42 to 52 ton. These heavy vehicles cause severe deterioration to the pavement and thus reduce its life.

Extensive researches have been conducted for the application of steel slag in broad areas of road construction. Steel slag contains significant amounts of free iron, which gives the material high density and hardness and makes it as a suitable artificial source of aggregates for road construction [7]. It can be used as an aggregate in surface layers and in unbound bases or sub-bases, due to its high strength and durability.

A few studies have tried to quantify the benefits of steel slag in reducing the failure factors through the subbase layer, but no firm conclusions can be drawn due to differences of results. Thus, an important need exists to quantify the benefits derived from stabilizing limestone layer with steel slag. On the other hand, until now, the steel slag is not used on a large scale in Egyptian roads construction compared to other countries in the region.

Thus, the main objective of this research is to study the effect of using steel slag that combined with limestone aggregates by different ratios on improving the mechanical properties of the unbound layer mixes and increasing the resistance for failure factors such as vertical deformations, vertical and radial stresses and vertical strains under overweight trucks loads. Hence determine the optimal steel slag ratio. In this study, experimental program was achieved to determine the mechanical properties of the mixes such as resilient modulus MR. Moreover theoretical program was achieved using MR that obtained from experimental work to determine the failure factors by the aid to the finite element method.

3. Literature review

The utilization of industrial by-products from the steel-making industry like blast furnace slag and steel slag has been established in a number of applications in the civil engineering industry. Production of steel, calls for the removal of excess silicon and carbon from iron by oxidation. In the production of steel, the furnace is charged with iron ore or scrap metal, fluxing agents, usually limestone and dolomite, and coke as both fuel and reducing agent. The carbon and silicon are removed as carbon dioxide and the remaining oxidized elements are combined with added lime to form steel slag. Steel slag is a hard, dense, abrasion resistant, and dark colored material. It contains significant amounts of free iron, giving the material high density and hardness. These properties make the steel slag particularly suitable aggregate used in road construction [8].

Application of slag in road construction relies on angularity and high shear resistance of their constituent particles, which make them suitable for several pavement layers. It should be mentioned that the superior frictional resistance properties of steel slag and its resistance to permanent deformation (rutting) often overshadow the potential of this material for cracking [9]. The subbase or subgrade soil can be lower quality because it is located at a greater distance from wearing surface, and the stresses it receives are less intense. Local materials which are the most economic can be used. Maslehuddin et al. [10] evaluated the mechanical properties and durability characteristics of steel slag aggregate in comparison with the crushed limestone stone aggregate. The results indicated that the durability characteristics of steel slag cement were better than those of crushed limestone aggregate. Similarly, some of the physical properties of steel slag aggregate concrete were better than those of crushed limestone aggregate concrete, though the unit weight of the former was more than that of the latter.

A study obtained by Shaopeng et al. [11] aimed to explore the feasibility of utilizing steel slag as aggregates in stone mastic asphalt (SMA) mixtures. Results indicated that the resistance to low temperature cracking of SMA mixture were improved by using steel slag as an aggregate. In-service SMA pavement with steel slag also presented excellent performance. In order to reuse the industrial solid wastes widely distributing in China, a new type of steel slag–fly ash–phosphogypsum solidified material was prepared by Weiguo et al. [12] to be engineered as road base material. Results obtained that its dry density increased with the increase of the ratio of steel slag–fly ash. The splitting strength and resilience modulus of steel slag–fly ash–phosphogypsum were equivalent or superior to those of those typical road materials, The engineering of steel slag–fly ash–phosphogypsum solidified material as road base material should be an alternative approach to massively reuse those three solid wastes.

Perviz et al. [13] presented the influences of the utilization of steel slag as a coarse aggregate on the properties of hot mix asphalt. Four different asphalt mixtures containing two types of coarse aggregate (limestone; steel slag) were used to prepare Marshall specimens and to determine optimum bitumen content. It was observed that the stiffness modulus values of the mixtures containing steel slag coarse aggregate were higher than mixtures with limestone coarse aggregate at all testing temperatures. In terms of creep stiffness, the values of steel slag mixtures were substantially higher than that of the control mixtures. The higher creep stiffness of the mixtures with steel slag coarse aggregate indicated better rutting resistance. Moreover, volume resistivity values demonstrated that the electrical conductivities of steel slag mixtures were better than that of limestone mixtures.

Bagampadde and Al-Abdul Wahhab [14] evaluated the effectiveness of steel slag aggregate by resilient modulus, split tensile strength, stability, fatigue, and permanent deformation tests. In their study, it was concluded that mixes with steel slag in the coarse portion and limestone in the sand and filler portions prepared using polymer modified asphalt show high fatigue life and high resistance to permanent deformation. Asi et al. [15] investigated the feasibility of utilization of steel slag in asphalt concrete mixes by indirect tensile strength, resilient modulus, rutting resistance, fatigue life, creep modulus, and stripping resistance tests. It is found that replacing up to 75% of the limestone coarse aggregate by steel slag aggregate improved the mechanical properties of the mixes.

Generally, the vast majority of the researches, which dealt with the use of steel slag in the pavement construction, investigated the effect of steel slag as coarse aggregate in hot mix asphalt concrete. There is a paucity of researchers dealing with steel slag evaluation as subbase layer.

4. Research approach

In flexible pavement, wheel loading is firstly met with wearing course in flexible pavements. The magnitude of load is distributedly transmitted to lower layers and to subgrade lastly. Flexible pavements must also carry the axle loading of vehicles as safety and economically. Layered flexible pavements are designed by considering criteria as design life, traffic volume and the strength of the subgrade. The flexible pavements are composed of wearing course, base course, subbase and subgrade layers.

For many designs the main function of the subbase of a flexible pavement is to reduce the building cost. The objective is to achieve required pavement thickness with the possible economic materials. The entire thickness could be constructed with a high-quality material such as that used in the base course. However it is generally preferred to make the base thinner and substitute a subbase layer of poorer quality material, although the total pavement thickness may have to be increased. The poorer the quality of the material that is used, the greater will be the thickness required to tolerate and transmit the stresses. Another function of subbase is to provide a transition layer between the material of the base course, which is generally coarse-grained, and that of the subgrade, which is usually much finer. The subbase also serves to absorb detrimental deformations in the subgrade such as volume changes associated with variations in water content, which might eventually be reflected in the pavement surface. Another function of the subbase is to drain off any water that infiltrates from the surface and to prevent water from the fill from rising towards the base course due to capillarity [16].

An experimental program was presented in this research, aimed to study the effect of using steel slag combined with limestone aggregates in different proportions on the density and sheer strength characteristics. The experimental program was achieved utilizing the standard proctor test and California bearing ratio (CBR) to determine the best mixing ratio. With the aid of mixes strength a theoretical analysis was achieved using a finite element (FE) computer program (FENLAP) for the purpose of estimating the deflection, vertical strain, vertical and radial stress in the blended layer. The research approach contains the following steps.

4.1. Materials and experimental work

Two types of aggregates were used in this study. The first one is the steel slag aggregate taken from Hadeed Ezz Al Dekheala

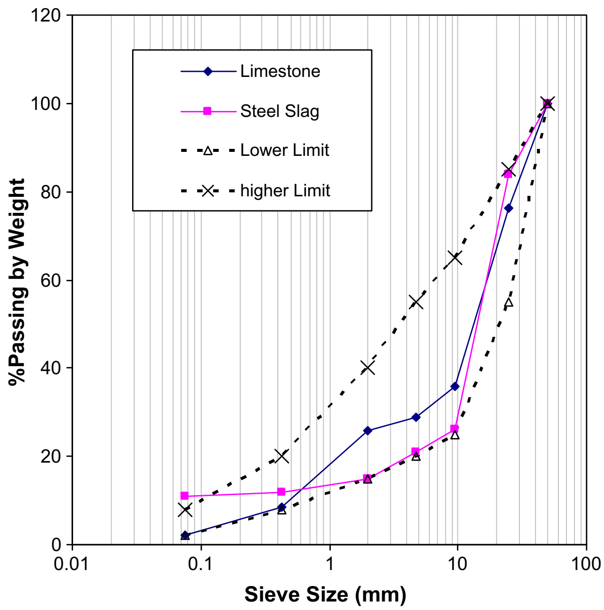

Figure 1 Grain size distribution of limestone and steel slag.

factory. This type of aggregate is used generally in cement production in Egypt. The second type is limestone aggregate taken from the general Nile Company of desert roads. The origin of the limestone aggregates is EL-Suez area, in the northeast Egypt. The grain size distribution for limestone aggregate as well as steel slag aggregates are presented in Fig. 1. An experimental program was carried out to investigate the influence steel slag percentage on the values of mixes density and strength to determine the optimal mixing ratio.

4.2. Theoretical program

Utilization mixes resilient modulus obtained from experimental work, the theoretical calculations were carried out using Finite Element method (FENLAP Computer program). The FENLAP was made by the University of Nottingham–England and developed at the University of Dresden–Germany. Using this computer program, axial symmetrical stress and deformation behavior could be calculated for the different layers of the pavement. Features of the finite-element FENLAP model include materials, loads, boundary conditions, element types, and model geometry. The theoretical program was

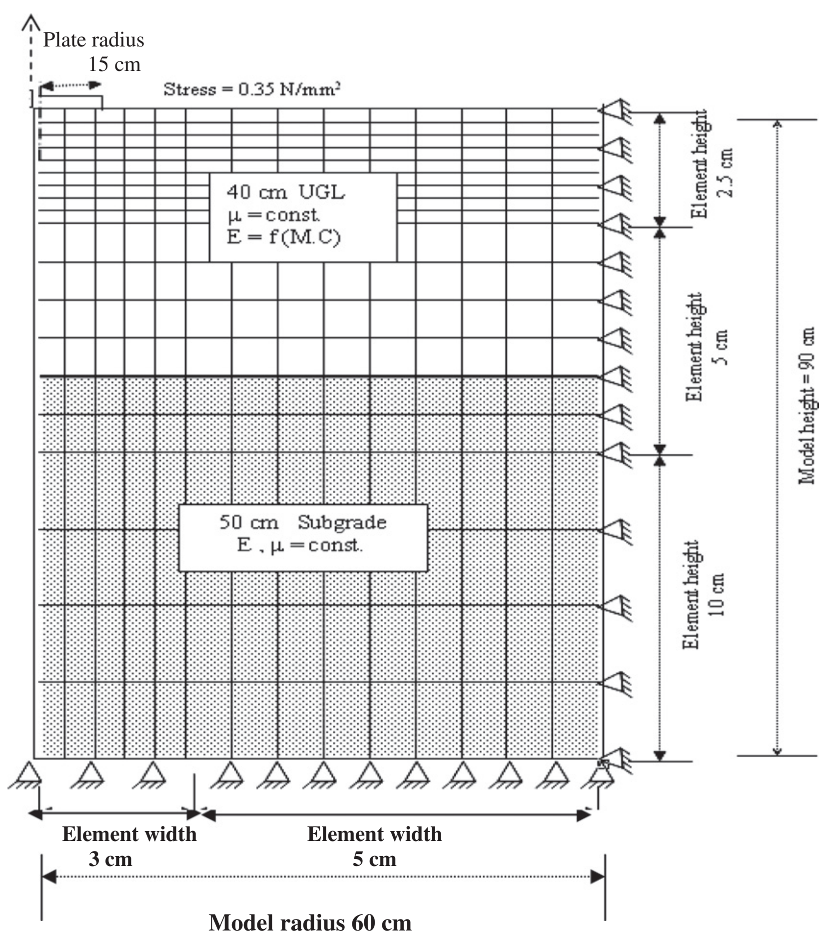

Figure 2 The geometry of the axial symmetric model.

designed to cover some factors that influence the deformation, stress and strain behavior of pavement such as wheel load and resilient modulus (MR) of granular layer.

4.3. Strength and stiffness correlations

The elastic modulus of unbound pavement materials is most commonly characterized in terms of the resilient modulus (MR). The resilient modulus is defined as the ratio of the applied cyclic stress to the recoverable (elastic) strain after many cycles of repeated loading and thus is a direct measure of stiffness for unbound materials in pavement systems. Various correlations between MR and other soil properties are used around the world [10]:

- A widely used empirical relationship developed by Heukelom and Klomp (1962). This equation is restricted to fine grained materials with soaked CBR values of 10 or less and used in the 1993 AASHTO Guide is [17]:

$$MR(psi) = (1500)(CBR) \quad (1)$$

- US Army Corps of Engineers (Green and Hall, 1975) [17]

$$MR(psi) = 5,409(CBR)^{0.71} \quad (2)$$

- South African Council on Scientific and Industrial Research (CSIR)[17]

$$MR(psi) = 3000(CBR)^{0.65} \quad (3)$$

- Transportation and Road Research Laboratory (TRRL)[17]

$$MR(psi) = 2555(CBR)^{0.64} \quad (4)$$

- The Georgia department of transportation tested a number of granular materials in repeated load triaxial test following the AASHTO procedure to create a database so that the resilient modulus can be predicted. A typical equation for stabilized lime stone is as follows [18]:

$$MR(psi) = 3116(CBR)^{0.49} \quad (5)$$

4.4. Applied vertical pressure

In this study, it's considered that an 18000 lb; single-axle load applied to the pavement on two sets of dual tires. The dual tires are represented as two circular plates each 4.52 in. in diameter, spaced 13.57 in. apart [10]. This representation corresponds to a contact pressure of 0.5 N/mm^2 on asphalt surface layer. The vertical stress is calculated at the surface of the granular layer using the Bisar-Linear elastic program where decreases to 0.35 N/mm^2.

4.5. The finite element model

For this research, the whole mesh has a dimension of 0.6 m × 0.9 m in the radial direction represented a half of the model due to symmetric. This model contains unbound granular layer (UGL) of 0.4 m and silt subgrade soil of 0.5 m in depth. This mesh consists of 15 columns and 20 rows (266 elements). In the vertical axis, the height of the elements is 2.5 cm up to level 0.2 m after that increased to 5 cm up to level 0.5 m later 10 cm to the bottom of subgrade. The width of the elements is 3 cm up to column of 0.15 m then increased to 5 cm to the mesh end. Fig. 2 illustrates the geometry of the axial symmetric model.

5. Analysis of experimental results

5.1. Aggregate properties

Some of the important properties of the steel slag and crushed limestone aggregates are summarized in Table 1. The physical properties of steel slag aggregates are superior to those of crushed limestone aggregates. The major difference between the steel slag and crushed limestone aggregate is the bulk specific gravity. The bulk specific gravity of the steel slag aggregates is 3.34 while it is 2.4 for the crushed limestone aggregates. The water absorption of the steel slag aggregates is almost one-fourth of that of the crushed limestone aggregates. The values of chemical composition of steel slag presented in Table 1 are based on the information gained from Hadeed Ezz Al Dekheala Factory.

Table 1 Properties of used steel slag.

Property	Steel slag	Limestone
Physical properties		
Porosity (%)	2.5	13
Unit weight (gm/cm^3)	1.62	1.75
Los Angeles abrasion (%)	20	40
Angle of internal friction (°)	45	23
Bulk specific gravity	3.34	2.4
Water absorption (%)	0.85	2.2
Chemical composition		
$CaCO_3$	10.0	95.0
SiO_2	1.0	5.0
Fe_2O_3	89.0	0.0

Table 2 Optimum moisture content (OMC) and maximum dry density (MDD) for various blended mixes.

Blend sample type	Optimum moisture content% (OMC)	Maximum dry density (MDD) × 10^{-5} N/mm^3
Pure limestone	16.00	1.785
10% steel slag + 90% limestone	16.00	1.850
20% steel slag + 80% limestone	14.00	1.940
30% steel slag + 70% limestone	12.50	2.030
40% steel slag + 60% limestone	11.00	2.100
50% steel slag + 50% limestone	12.60	2.150
60% steel slag + 40% limestone	11.00	2.230
70% steel slag + 30% limestone	11.00	2.300
80% steel slag + 20% limestone	10.00	2.360
90% steel slag + 10% limestone	10.20	2.456

Table 3 California bearing ratio and resilient modulus.

Steel slag percentage (%)	0.0	40	50	60	70	80
CBR (%)	14	56	74	195	370	270
MR (MPa)	800	1400	1800	2900	4000	3300

5.2. Aggregates gradation

To obtain the gradation of both steel slag and limestone aggregates, a dry samples were taken and sieved. An automatic sieve shaker was used for this purpose. The Egyptian code has specified a certain gradation limits that suitable as subbase soil. The sieve analysis test results for two aggregates and the specification limits are shown in Fig. 1.

5.3. Standard proctor test

The two aggregates used in this study were separated into different sizes by sieving and then reconstituted to obtain the target gradations. Ten blended mixes samples by weight were prepared. The ten blended mixes were tested to evaluate the effect of steel slag content to limestone aggregate on the optimum moisture content (OMC) and the maximum dry density (MDD). Table 2 shows the obtained results.

As shown in Table 2, with the increase of the steel slag percentage the maximum dry density (MDD) increases, while in the same time the construction costs of layer increases. Thus, to get the best density for the layer and the least construction costs it is recommended to use a blended mix of 60–70% steel slag percentage (SSP) where higher MDD of 2.3×10^{-5} N/mm^3 is obtained. While with increasing SSP to 80%, or 90%, a very slight increase in MDD occurs. The importance of this slight increase in mixes density is not effective compared with the increase in the total cost of the steel slag if increased by 10% or 20%.

5.4. California bearing ratio and resilient modulus

Five blended mixes were tested to evaluate the effect of steel slag percentage on the mixture strength. To calculate the resilient modulus equation (5) was chosen because of Georgia department of transportation [18] concentrated on description of non-linear stress–strain behavior of unbound subbase materials. The main goal of this equation was the calculation of the permanent deformation for unbound granular materials (UGLs) in asphalt pavement constructions. This required a model in which both the stress dependent resilient behavior as well as the stress dependent permanent strain development were considered. Moreover, the analysis of this equation explained, how the results of the resilient calculations can be used to explain the development of permanent strain in the substructure.

According to Eq. (5), the Resilient Modulus for each mix was calculated. The CBR values and corresponding resilient modulus are shown in Table 3.

It can be observed that the increase of steel slag percent up to 70% leads to an increase of California bearing ratio (CBR) and consequently, the resilient modulus. While for 80% steel slag a sudden drop in the value of (CBR) occurs. This drop may be due to the bad interlock between steel slag aggregate particles. This percentage obtained is similar to percentage by Farrand and Emery [3]and Asi et al. [15].

6. Analysis of theoretical results

It is possible to evaluate the behavior of granular subbase using theoretical methods, by recording the relationship between stress and strain for each material. For this purpose, the experimental tests are required to determine the material characteristics (material parameters such as MR). The finite element method (FEM) is widely accepted as a numerical method for analysis and design almost of all branches of engineering. The development of a Finite Element model to accurately predict the performance of road section is attractive because the model can be used to examine various experimental test configurations that have not been modeled experimentally.

6.1. Linear-elastic relationship

Calculations of stresses and strains of a pavement require a mathematic relationship between deformation and the effective load or stress in form of a substance law. From Hooke law. This simple relation of linear-elastic theory is the bases for calculation of stress, strain and deformation of homogenous-isotropic half space under influence of single load during Boussinesq equations. There are computer programs are made on the basis of multi-layer theory. Using these programs, strain and displacement at selected Points in pavement section can be calculated. The required input data are height of each layer, modulus of elasticity and Poisson ratio for each layer. The relationship between stress and strain is as follows [19]:

$$\varepsilon_1 = \frac{1}{E} * (\sigma_1 - \mu * \sigma_2 - \mu * \sigma_3) \tag{6}$$

$$\varepsilon_3 = \frac{1}{E} * (\sigma_3 - u * \sigma_1 - u * \sigma_2) \tag{7}$$

$$\varepsilon_v = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \tag{8}$$

$$\varepsilon_s = \frac{\sqrt{2}}{3} \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_1 - \varepsilon_3)^2 + (\varepsilon_2 - \varepsilon_3)^2} \tag{9}$$

$$P = \frac{1}{3} * (\sigma_1 + \sigma_2 + \sigma_3) \tag{10}$$

$$q = \frac{1}{\sqrt{2}} * \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} \tag{11}$$

where ε_1, ε_2, ε_3 are the main strains; εv the volumetric strains; εs the shear strain; σ_1, σ_2, σ_3 the main stresses (kPa); q the deviator stress (kPa); p the average main stress (kPa); and μ is the Poisson's ratio.

6.2. Non-linear substance models

The concept non-linear stress–strain behavior of loose aggregate could be understood from description of digressive and progressive dependency of this relation. Mainly, loading of unbound loose aggregate happen in elastic region, so it could be in suitable field- and labor tests increasing in deformation resistance of compacted aggregate layer with increasing the load. Digressive behavior of stress–strain curve cause an increase in deformation resistance of materials and consequently increases in elastic modulus with increasing stress level [19].

6.3. Unbound granular layer UGL

At the Highway Institute, Dresden University of Technology, investigations of the non-linear elastic stress–strain-behavior of UGL have been carried out for the past 20 years. As a result of the data from repeated load triaxial test a new elastic material law – Dresden-Model was developed. Modified plate-bearing test with cyclic loading were carried out on UGL. To check the validity of the elastic Dresden-Model the surface deflection induced by plate bearing tests was predicted by using the FE-program (FENLAP) [19].

6.4. Effect of steel slag percentage

In finite element analysis, the structure and other conditions have to be correctly modeled to obtain reasonable response results. Features of the finite element FENLAP model include material models, load model, boundary conditions, element type, and model geometry. The finite element model is as discussed in Section 4.5. Two dimensional linear finite element analysis under plane strain condition have been presented for the studied model. The unbound granular materials of subbase layer and subgrade soil have been discretized by eight noded isoparametric finite elements.

The theoretical analysis using Finite-Element Computer program "FENLAP" has been done to obtain the effect of steel slag percentage (SSP) on improving the resistance of deformation, stress and strain through layer mixes under increased axle loads. Four different mixes with steel slag percentage of 0.0%, 40.0%, 60.0%, 70.0% are considered. The resilient modules for each steel slag percentage which required in FENLAP program are obtained from the experimental work as shown in Table 3. The values of deflection, strain and stress are evaluated and plotted against vertical depth.

Fig. 3 illustrates the maximum deflection of different mixes as a function of SSP. It is clearly noted that the layer deflection decreases by increasing the steel slag percentage. The difference in maximum deflection according to SSP decreases with increasing the layer depth. The relationship between the vertical strain through the layer depth and the SSP is shown in Fig. 4. The results illustrate that by increasing the steel slag percentage the vertical strain values decrease. The maximum increase of vertical strain is occurred in 10–15 cm from the surface of the layer.

Fig. 5 represents the relationship between the vertical stress and the subbase depth. It can be considered that the vertical stress decreases with the increase of depth. The changing in steel slag percentage has not any obvious effect on reducing the vertical stress through the depth especially at the top of the layer. Fig. 6 shows the values of radial stress for different blended mixes, this figure indicates that by increasing the steel slag percentage a little increase in radial stress is achieved. The maximum radial stress occurs at the top and bottom of the subbase layer while the minimum radial stress occurs at the middle of the layer. The radial stress changes from negative

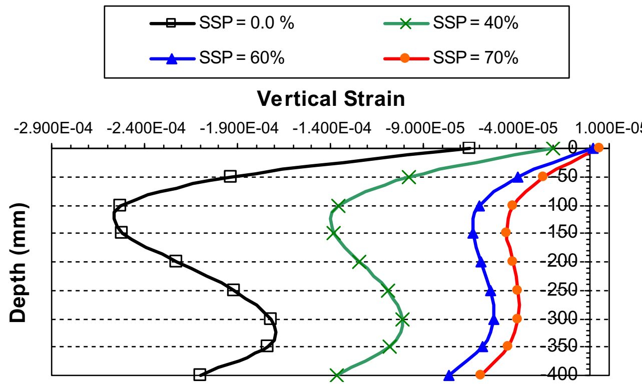

Figure 4 Effect of SSP on subbase vertical strain.

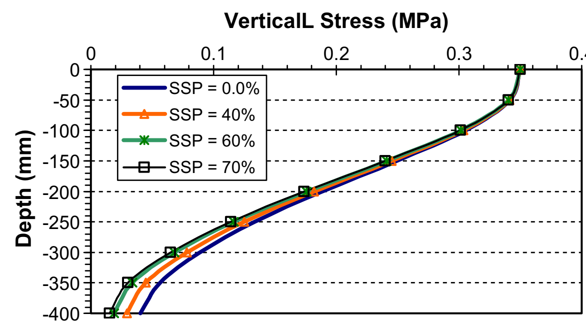

Figure 5 Effect of SSP on subbase vertical stress.

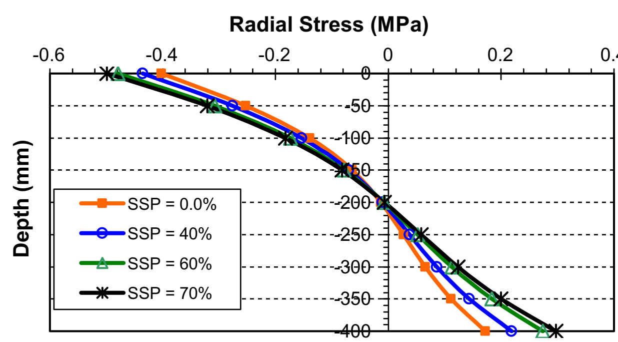

Figure 6 Effect of SSP on subbase radial stress.

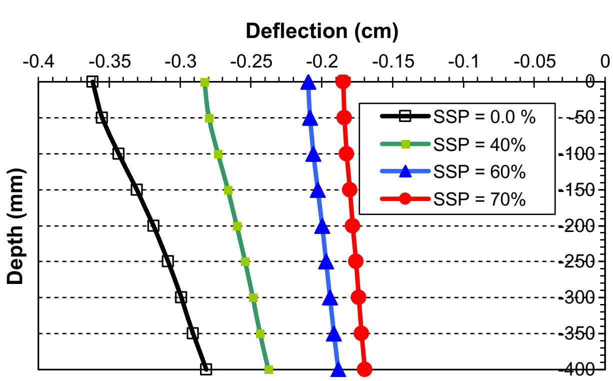

Figure 3 Effect of SSP on subbase deflection.

(tensile stress) to positive (compression stress) through the layer depth.

6.5. Effect of vertical applied load

Heavy load application is considered a major reason of pavement distresses. In the past decades, many researchers have obtained damage of road resulted from repeated loads application to highway pavements based primarily on the intensity and frequency of axle loads. As the axle load of heavy vehicles has increased, the need to evaluate the effects of heavy axle load on pavement performance becomes urgent.

Different axle loads are considered in this research; the standard 18 kips (8.2 tons) axle load; the maximum allowed axle load in Egypt is 10 tons according to the Egyptian code for urban and rural highways. Three wheel loads of 6, 8 and 10 tons are taken to investigate the effect of the applied load on pavement response. Fig. 7 illustrates the relationship between the vertical deflection and the layer depth where the highest deflection occurs under the highest wheel load. Moreover, the rate of deflection is nearly constant during the layer depth.

Fig. 8 shows the change of the vertical strain during the depth of the layer where with increasing the wheel load, the vertical strain decreases above a reversing point which located in the middle of the layer thickness. Below this point, the vertical strain increases with increasing the wheel load. The relationship between radial stress and the layer depth is shown in Fig. 9. At the top of the layer the radial stress is negative (tensile stress) this stress changes to positive in the lower half of the layer where the radial stress equals zero at the intermediate of layer's depth. With increasing the wheel load the radial stress increases at the top and bottom of the layer.

6.6. Effect of horizontal distance from load center

Fig. 10 illustrates the effect of horizontal distance on the maximum deflection for different mixtures. It should be noted that the maximum deflection lies under the load center and reduces with increasing of the horizontal distance. Moreover, increasing the steel slag percentage (SSP) decreases the deflection up to a horizontal distance of 60 cm. For distances longer than 60 cm, the deflection increases with the increase of (SSP). Thus

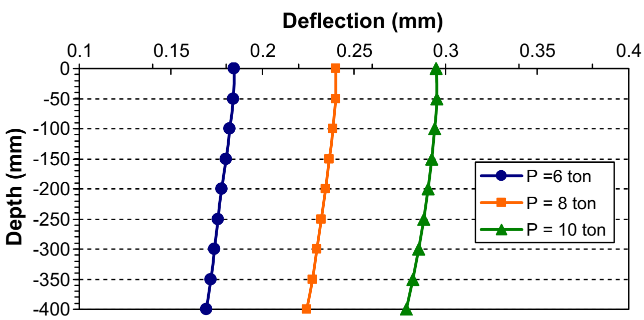

Figure 7 Effect of vertical applied load on deflection.

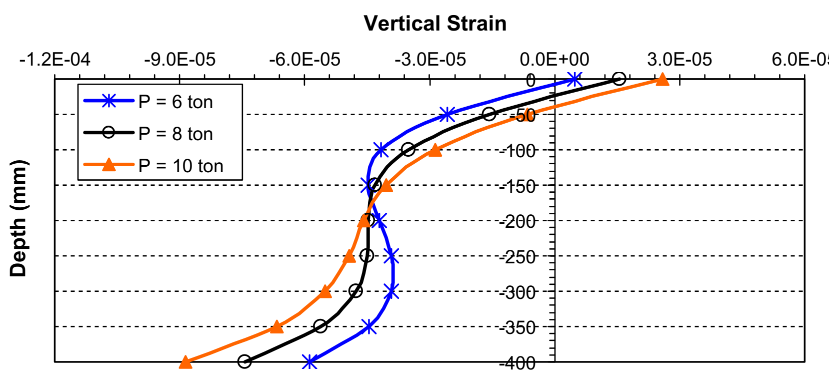

Figure 8 Effect of vertical applied load on vertical strain.

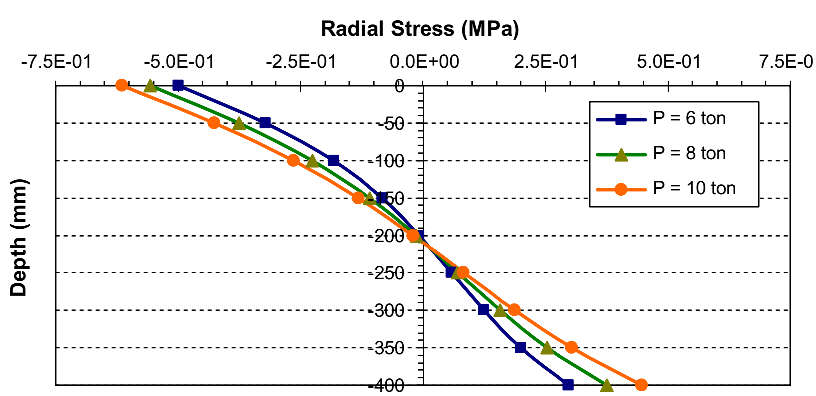

Figure 9 Effect of vertical applied load on radial stress.

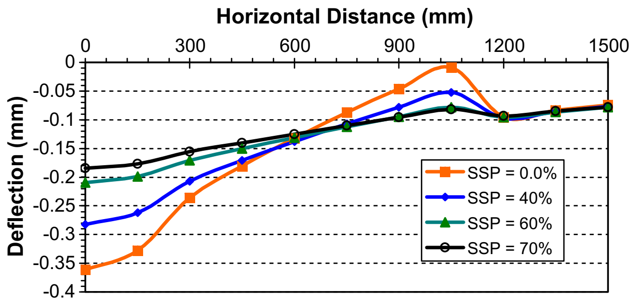

Figure 10 Effect of horizontal distance on deflection.

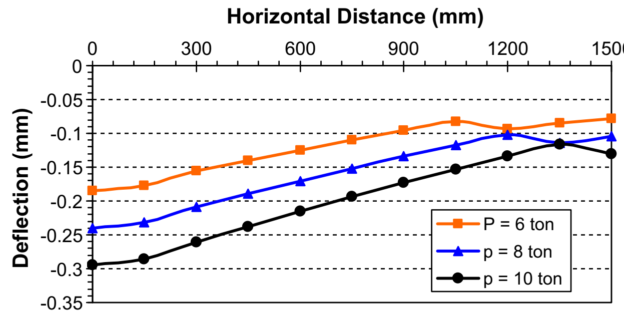

Figure 14 Effect of horizontal distance on deflection.

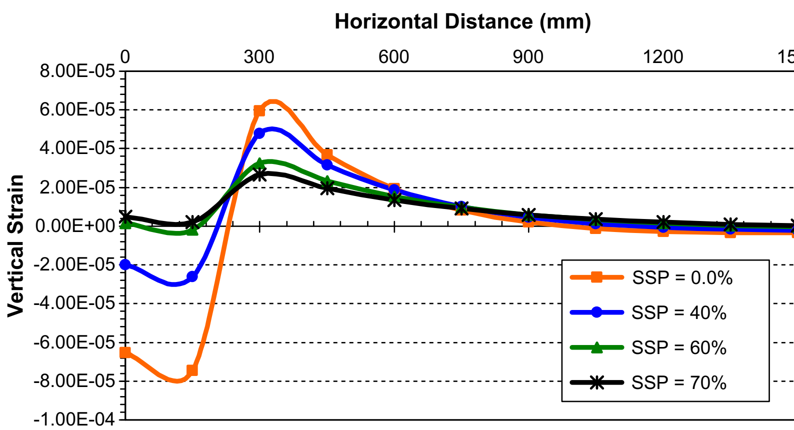

Figure 11 Effect of horizontal distance on vertical strain.

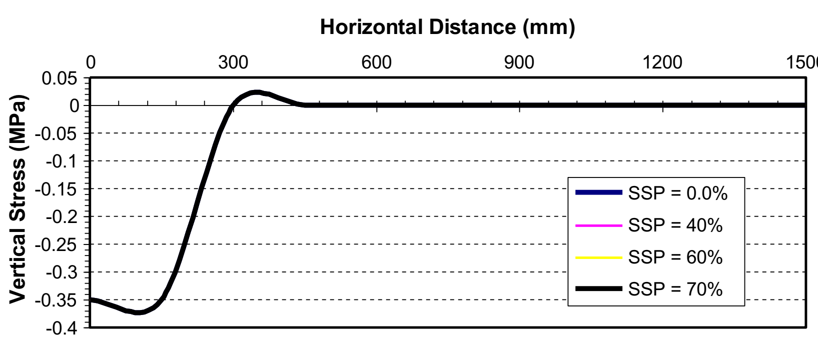

Figure 12 Effect of horizontal distance on vertical stress.

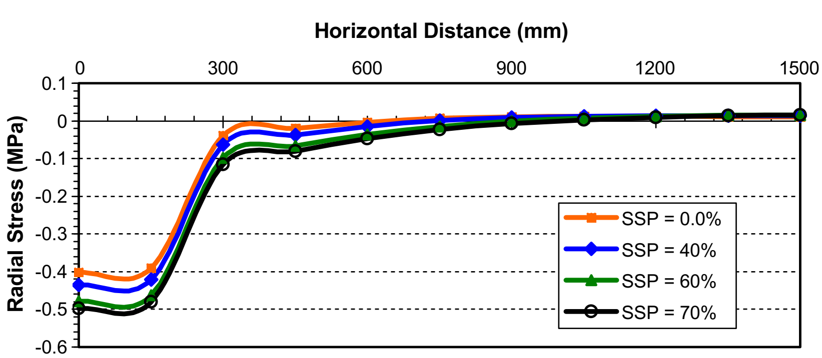

Figure 13 Effect of horizontal distance on radial stress.

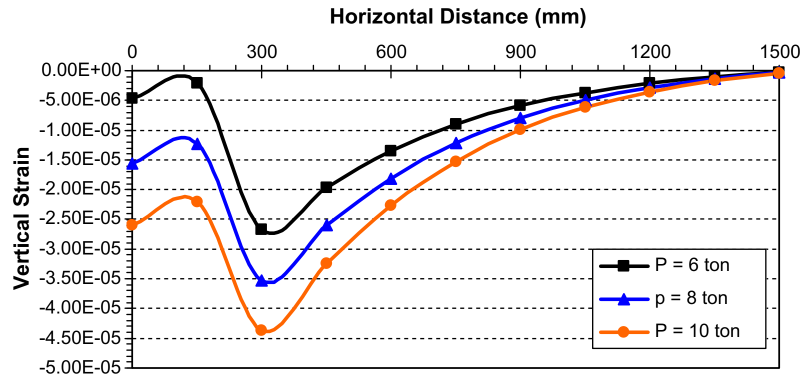

Figure 15 Effect of horizontal distance on vertical strain.

the advantage of steel slag addition is clearly manifested in reducing the rutting through about 60 cm from the load impact point.

Effect of horizontal distance on vertical strain as a function of the steel slag percentage is shown in Fig. 11. The vertical strain decreases with increasing the steel slag percentage. The relation could be divided into two phases, the first phase that occurs up to 30 cm from load center where the vertical strain is negative. In the second phase (after 30 cm from load center) the vertical strain changes to be positive. The rate of strain after horizontal distance of 90 cm is constant. Thus the steel slag plays a great role in reducing the rate of deformation during horizontal distance.

The relationship between horizontal distances and vertical stress is shown in Fig. 12. It is concluded that the slag percentage has no obvious effect on the vertical stress along the horizontal distance where the maximum vertical stress lies under the load center. After about horizontal distance of 45 cm the vertical stress vanishes (becomes zero). Fig. 13 shows the effect of steel slag percentage of subbase layer on radial stress along the horizontal distance. The maximum radial stress is accumulated under the load center. Where with increasing the horizontal distance the radial stress decreases, while with increasing the steel slag percentage the radial stress increases.

Fig. 14 represents the effect of horizontal distance on the maximum deflection as a function of wheel load. The deflection increases with the increase of wheel load and decreases with the increase of the horizontal distance. The rate of deflection decreasing is almost the same for each wheel load. The effect of horizontal distance on vertical strain as a function of applied wheel load is shown in Fig. 15 where the maximum vertical strain occurs at 30 cm from the load center. Furthermore, with increasing the wheel load the vertical strain increases. The influence of wheel load on vertical strain is faded at a distance of 150 cm.

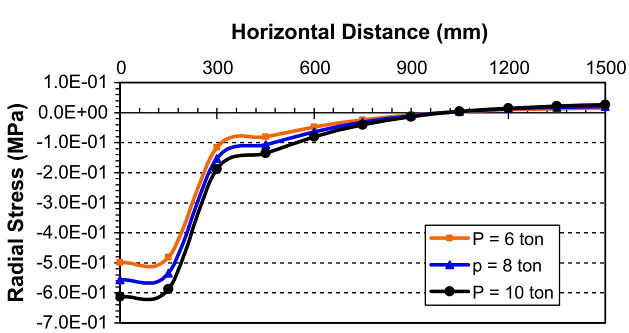

Figure 16 Effect of horizontal distance on radial stress.

Fig. 16 shows the effect of the horizontal distance on radial stress as a function of wheel load. The maximum radial stress accumulates at load center where decreases with increasing the horizontal distance from the load center. Radial stress goes almost constant and then decrease with increasing the horizontal distance for all wheel loads.

Generally, Adding steel slag to the limestone aggregates up to 70% obviously improves the resistance to deflection and vertical strain through layer depth and along horizontal distance according to increased axle loads. For horizontal distance up to 60 cm, increasing steel slag percentage increases resistance of deflection, this may be due to the good interlock between steel slag aggregate particles which provides good load transfer to weaker aggregate layer.

7. Conclusions

This study is carried out to investigate the effect of using steel slag mixed with limestone aggregate on increasing the density and strength of subbase layer. Second objective of this research is studying the effect of steel slag on the resisting of failure factors such as deflection, stress and strain. Third objective of this research work that presented in this study is determining the optimal steel slag ratio. Based on the result of this study, the following conclusions are summarized:

1. Increasing the steel slag percentage (SSP) to the limestone in the blended mix increases the mechanical properties such as maximum dry density, California Bearing Ratio and resilient modulus. The best density and strength for the layer with the least construction costs obtained at a blended mix of 70% steel slag percentage to 30% limestone.
2. Adding steel slag to the limestone aggregates increases the resistance to deflection and vertical strain. While, with increasing the steel slag percentage a little increase in radial stress is achieved. Moreover, the effect of SSP on the vertical stress along the horizontal distance can be neglected. The advantages of steel slag addition are clearly manifested in reducing the rutting and minimizing the rate of deformation through about 60 cm from the load impact point.

3. With increasing the depth of the subbase layer, the vertical stress decreases and the deflection is almost constant while the radial stress changes from negative (tensile stress) to positive (compression stress) through the layer depth. The maximum increase of vertical strain is occurred in 10 to 15 cm from the surface of the layer. By increasing the wheel load, the deflection increases and the vertical strain decreases above a reversing point which locates in the middle of the layer thickness. Furthermore, increasing the wheel load increases the radial stress at the top and bottom of the layer.
4. Maximum deflection, radial stress and vertical stress lie at the load center and reduce with increasing of the horizontal distance from the load. The vertical strain is negative in the first 30 cm from load center and then changes to be positive. The rate of strain after 90 cm is constant. For horizontal distance up to 60 cm, increasing SSP increases resistance of deflection. After about horizontal distance of 45 cm the vertical stress vanishes (becomes zero). Radial stress goes almost constant and then decreases with increasing the horizontal distance for all wheel loads.

In general can be said that the use of steel slag especially at optimal ratio improved the subbase layer density, strength and failure resistance especially for horizontal distance of 60 cm from load center. Thus, this research recommends utilizing industrial by-products such as steel slag especially in developing countries to reduce the use of primary aggregate and thus minimize the cost of road construction.

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