Research Article

Developing a Higher Performance and Less Thickness Concrete Pavement: Using a Nonconventional Concrete Mixture

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During the last three decades, concrete pavement or rigid pavement became a widely used alternative of flexible pavement (asphalt pavement) at freeways and highways with high traffic of heavy vehicles, due to its durability, long life, and less need of maintenance; however, the cost of construction for rigid pavement is very high compared to asphalt pavement. Developing a new concrete mixture to increase the performance and reducing the required thickness of concrete pavement became an important issue in rigid pavement design in order to reduce the high construction cost. In this study, a new concrete mixture was developed using specific amounts of steel fibers and steel slag (as a supplementary cementing material to replace a part of the cement). Several mixtures with different concentrations of fibers were prepared, and samples were tested for workability, early flexural strength, and ultimate flexural strength. The results showed that the new concrete mixture could achieve an increase in flexural strength between 48.9% and 50.5% compared to normal concrete mixture without steel fibers and steel slag, with minimum acceptable workability, and therefore, the required pavement thickness could be decreased by more than 24%.

1. Introduction

Concrete is one of the construction materials that are widely used around the world. In transportation sector, rigid pavement is an important application of concrete, since using concrete as a surface pavement is more durable than asphalt pavement, requiring less maintenance and having longer life.

Conventional concrete usually experiences failure caused by the breakdown of the bond between paste and aggregate, and this reduces the flexural strength which is one of the principal factors in concrete pavement design [1]; therefore, the enhancement in flexural can be used to improve the performance sections and to reduce the required thickness of the pavement [2].

During last three decades, the use of different types of fibers in concrete was investigated in order to enhance the flexural strength of concrete and to transform the cement matrix from a brittle to a ductile material; however, it must be well noted that the benefits of adding fibers to concrete are influenced by the content and type of fibers in use [3, 4].

Steel fiber is a relatively new construction material. It has been proved as a reliable construction material that has superior performance effects when used in concrete and could improve the characteristics of concrete, compared to the conventional normal concrete in the following properties: higher flexural strength, better tensile strength, higher shock resistance, and crack resistance [5, 6]; all of these gained benefits are very vital in developing a better rigid pavement. The effectiveness of improving these parameters depends, among other things, on the type of fiber, size, aspect ratio, and volume fraction of fibers [6].

Another material that is used to enhance some of the properties of concrete is steel slag, which is obtained from the steel manufacturing plants as a waste material [7]. One of the main benefits of using steel slag in concrete as a supplementary material is to increase the flexural strength of the concrete, which is one of the principle factors in rigid pavement design [8].

Flexible pavements (asphalt pavements) are widely used around the world and in general consist of three layers: subgrade soils, base course, and asphalt surface. The asphalt surface

layer provides the comfortable driving environment, and the subgrade layer ensures the structural deformation stability [9]. In case soil-rock mixture (SRM) materials are used as a subgrade, the physical composition and stress state of SRM materials have a crucial influence on the mechanical properties of the subgrade and play a vital role in improving this layer [10].

Due to long-term exposure to environmental factors and traffic loads, the asphalt surface weakens gradually [9]. Therefore, the rigid pavement was developed in order to be used as an alternative to flexible pavement in roadways where severe exposure conditions and high traffic loads exist. Rigid pavement consists of a cement concrete slab (concrete pavement), below which a granular base or sub-base course may be provided. Providing a good base or sub-base course layer under the concrete slab increases the life of pavement and therefore works out more economical in the long term [11].

The factors that are considered by the American Association of State Highway Transportation Officials (AASHTO) for determining the thickness of the rigid pavement (concrete pavement) are [12]

(1) Pavement performance, which depends on the initial and terminal serviceability index

(2) Subgrade strength, which is given in terms of the Westergaard modulus of subgrade reaction (the load in kN/m^2 divided by the deformation in inches)

(3) Sub-base strength, which depends on the type of used materials (suitably stabilized materials or graded granular materials)

(4) Traffic, which is given in terms of equivalent single-axle loads (ESALs)

(5) Drainage, which depends on the quality of drainage and the percent of time the pavement structure is exposed to moisture levels approaching saturation

(6) Reliability, which depends on overall standard deviation and reliability level

(7) Concrete properties, which is given in terms of its flexural strength (modulus of rapture); the flexural strength in concrete pavements would permit them to sustain a beamlike action across minor irregularities in underlying materials [13]

In this study, a new concrete mixture is developed in order to produce a higher flexural strength concrete that can be used to achieve higher performance and less thickness rigid pavement. In order to achieve this goal, different mixtures were produced by adding steel fibers and using the steel slag as a supplementary material, simultaneously, with different concentrations. Generally, these materials are used separately in concrete industry to enhance some properties of concrete, but in this study, both of these materials are used simultaneously with specific amounts in order to enhance the flexural strength of concrete in rigid pavement.

2. Literature Review

During the last three decades, several studies have addressed the rigid pavement and improving the performance of rigid pavement by using different types of fibers. Some of these studies investigated the use of steel fibers to increase the performance and decrease thickness of rigid pavement.

One of these studies was conducted by Elsaigh et al. [14]. This study aimed to evaluate the use of steel fiber reinforced concrete in road pavements and to compare its performance with normal concrete without fibers and slag under traffic loads. Road trial sections were tested under in-service traffic and the performance of the pavement was analyzed. The results showed that a 25 percent thickness reduction in pavement is possible by using steel fibers.

Another study was conducted by Shireesha et al. [15]. The study analyzed the effects of steel fiber reinforced concrete. Concrete mixes were prepared using M40 grade concrete and hooked-end glued steel fiber with aspect ratio of 80. Fibers were added at a dosage of 0.5 percent, 1.0 percent, and 1.5 percent of volume fraction of concrete. The results showed that with a fiber volume fraction of 1.5 percent, the absorbed energy by the specimens during the tests was 8 times for 7 days and 10 times for 28 days higher than flexural toughness of normal concrete.

Likewise, a study was conducted by Rudresh and Shashank [16] to evaluate the various characteristics of M40 concrete after using steel fibers and polypropylene fibers individually. The study showed that the new concrete pavement mixture achieved higher flexural and tensile strength compared to normal concrete pavement. Moreover, the study concluded that a reduction in required thickness up to 30% could be achieved by the new mixture.

A study by Behbahani et al. [17] was conducted to evaluate the performance of steel fiber concrete. In this study, an optimum percentage of hooked-end steel fibers with dimensions of 0.75 mm in diameter and 50 mm in length was added in reinforced concrete beams with two different classes of concrete (30 MPa and 50 MPa). The results showed that adding 1 percent of steel fibers by volume of concrete will increase both flexural first-cracking strength and flexural toughness.

Similarly, a study by Shweta and Kavilkar [5] investigated the properties of steel fiber reinforced concrete like flexural and compressive strength. Tests were conducted to study the flexural and compressive strength of steel fiber reinforced concrete with varying aspect and varying percentage of fibers. In the conducted tests, five samples having different volumes of steel were used (0.5%, 1.0%, 1.5%, 2.0%, and 2.5%). The results of the study showed that adding 1.5 percent of steel fibers may lead to an increase in flexural strength by 36.7 percent.

In order to improve the flexural strength of concrete road pavement, several studies investigated the use of different types of fibers in concrete. Some of these studies tested the steel fibers; they concluded that a high flexural strength concrete could be achieved to some extent. In this study, a new steel fiber reinforced concrete mixture was developed by using the steel slag as a supplementary cementing material to replace a part of cement in the mixture in addition to using steel fibers in order to improve the flexural strength of the concrete, and therefore, a significant reduction in the required thickness of pavement could be achieved;

furthermore, the performance of the pavement could be improved, since the flexural strength is a principle factor in rigid pavement design.

3. Methodology

In order to develop a concrete mixture that can be used to achieve a higher performance concrete road pavement (rigid pavement) with less thickness, several concrete mixtures with different concentration of steel fibers and steel slag were prepared and tested for flexural strength and slump, as shown in the following procedure.

3.1. Cement. Portland cement type one was used to prepare the concrete mixtures, which is known as a normal Portland cement. This type of cement complies with BS 12:1991 [18], and it is the most used type of cement around the world. The ingredients of this type of cement are lime, alumina, silica, and iron oxide.

3.2. Aggregate. Generally, the aggregates that are used in concrete are divided into two types, based on size: fine aggregate particles which are less than 0.075 mm (sand size) and course aggregate particles which are larger than 4.75 mm (gravel size).

Quartz aggregates were used in this study as a coarse aggregate with maximum size of 19 mm and saturated surface dry density of 2750 kg/m^3. On the other hand, sea sand was used as a fine aggregate with 2.8 fineness modulus and saturated surface density of 2520 kg/m^3. The used aggregate satisfied the ASTM C33/C33M-18 ASTM standard for concrete aggregate [19].

3.3. Water. Natural water that is drinkable and has no pronounced taste or odor was used in concrete mixtures in order to prepare the samples. This water satisfies ASTM C1602/C1602M-18 standards for water used in concrete [20].

3.4. Superplasticizer. Conplast SP430 superplasticizer was used in this study for preparing concrete mixtures. This superplasticizer complies with BS 5075 part 3 [21] and with ATM C494 Type A and Type F [22]. Conplast SP430 is a chloride-free superplasticizer admixture based on selected sulphonated naphthalene polymers.

3.5. Steel Slag. A steel slag with specific gravity of 1.65 g/cm^3 was used as a supplementary cementing material to replace a part of the cement in the concrete mixture. This steel slag was produced in a steel factory as a result of burning the iron ore.

3.6. Steel Fiber. Hooked-end shape steel fibers were used in this study, as shown in Figure 1. The length, diameter, and aspect ratio (length/diameter) of these fibers are 60 mm, 0.8 mm and 75 mm, respectively, as shown in Table 1.
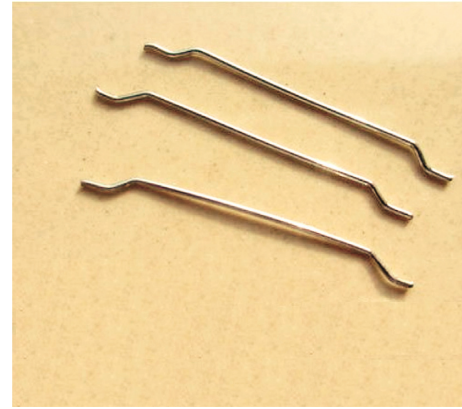

Figure 1: Hooked-end shape steel fibers.

3.7. Concrete Mixing. Initially, a control mixture (without using fibers and slags) was prepared using water cement ratio of 0.47, mixing ratio of 1 : 2 : 4 (cement : fine aggregate : coarse aggregate) by mass proportions, and superplasticizer of 3% (by mass of cement), as recommended by Hassouna and Abu-Zant [23].

Other mixtures were prepared using 20% steel slag (by mass of cementitious materials) as a supplementary material and adding 0.5%, 1.0%, 1.5%, and 2.0% steel fibers (by volume of concrete portions) as shown in Table 2.

In order to determine the optimum amount of slag that can be used, several experimental mixtures were prepared using 10%, 20%, and 30% of steel slag. The results showed that by adding more slag (up to 20%), higher flexural strength was obtained. By increasing the concentration of slag to more than 20%, there was a problem in mixing concrete components due to very low workability and formation of fiber balls. Therefore, 20% steel slag was selected to be used.

Six samples for compressive strength test (3 samples to be tested at 7 days and 3 samples to be tested at 28 days) and 3 samples for slump test were prepared using the concrete produced in each mixture.

3.8. Experimental Program. In order to test flexural strength, six concrete beams (150 mm × 150 mm × 900 mm) were prepared using the concrete produced from each mixture: three of them were tested at 7 days and the other three samples were tested at 28 days (total of 60 samples were tested), as shown in Table 3. The test was conducted using the procedure of ASTM C78 standards [24].

On the other hand, 30 samples were prepared and tested for workability of concrete (which is one of the most important properties of fresh concrete) using the slump test and following the ASTM C143/C143M-15a standards [25]. Three samples were prepared and tested using the concrete produced from each mixture.

3.9. Constraints. The main constraint the study faced is the presence of large amount of air voids when testing flexural strength for samples of concrete mixture with 2.0% steel

TABLE 1: Properties of steel fibers used in this study.

Shape	Diameter (mm)	Length (mm)	Aspect ratio (L/D)	Tensile strength (MPa)	Specific gravity
Hooked end	0.8	60	75	1050	7.8

TABLE 2: Amounts of slag, steel fibers, and superplasticizer in each mixture.

Mixture	Steel slag (% of mass of CM)	Superplasticizer (% of mass of cement)	Steel fibers (% of volume of concrete)
1	0	3	0
2	0	3	0.5
3	0	3	1.0
4	0	3	1.5
5	0	3	2.0
6	20	3	0
7	20	3	0.5
8	20	3	1.0
9	20	3	1.5
10	20	3	2.0

TABLE 3: Number of tested samples for slump and compressive strength.

Mixture	Number of slump samples	Number of compressive strength samples (7 days)	Number of compressive strength samples (28 days)
1	3	3	3
2	3	3	3
3	3	3	3
4	3	3	3
5	3	3	3
6	3	3	3
7	3	3	3
8	3	3	3
9	3	3	3
10	3	3	3
Total	30	30	30

fibers and 20% slag due to low workability of mixture. Therefore, three samples were repeated twice and compacted carefully. This did not affect the results of the study, since the three samples were finally tested successfully. Moreover, the mixture with 2.0% steel fibers was not recommended to be used by this study.

4. Discussion and Results

In order to improve the performance of the concrete pavement (rigid pavement), several studies investigated the use of different types of fibers in concrete mixtures; some of these studies tested the effects of adding steel fibers. The results showed an improvement in flexural strength when steel fibers were used. In this study, a new concrete mixture was developed by using steel fibers and replacing a part of the cement with steel slag.

Firstly, a control concrete mixture was prepared without adding any steel fibers or steel slag, to be used as a reference mixture in order to determine the effects of adding fibers and slag. Next, four more concrete mixtures were prepared using 0.5%, 1.0%, 1.5%, and 2.0% (by volume of concrete) of steel fibers. Then, five more concrete mixtures were prepared by using steel slag of 20% (by mass of cementitious material)

and using 0.0%, 0.5%, 1.0%, 1.5%, and 2.0% steel fibers. All mixture samples were tested for flexural strength at 7 and 28 days, and results were recorded, as shown in Table 4.

In order to test the workability of concrete mixtures, three samples from each mixture were tested using the slump test. The values of the slump varied from 190 mm for mixture 1 (0% slag and 0% fibers) to 2 mm for mixture 10 (2% fibers and 20% slag), as shown in Table 5.

The results of the slump tests showed that the highest slump value was obtained for the reference concrete mixture without any fibers and slag, with values of 190 mm. By increasing the percentage of the steel fibers in concrete mixtures, the slump value decreased gradually. The minimum slump value was 2 mm at mixture with 2.0% fibers, as shown in Figure 2. Adding 20% steel slag to each concrete mixture led to a decrease in the slump values for all concrete mixtures. This decrease varied from 10% for mixtures with 0.5% fibers to 60% for mixtures with 2.0% steel fibers, compared to mixtures with fibers only.

The minimum acceptable slump value for concrete pavement according to ACI 211.1-91 is 24 mm [26]; therefore, using concrete mixtures with 20% slag and steel fibers concentration less than 1.5% could be suitable for pavement which complies with ACI standards.

TABLE 4: Flexural strength results at 7 and 28 days.

Mixture	Steel slag (% of mass of CM)	Superplasticizer (% of mass of cement)	Steel fibers (% of volume of concrete)	Flexural strength at 7 days (MPa)	Flexural strength at 28 days (MPa)
1	0	3	0	1.8	4.8
2	0	3	0.5	2.7	7.4
3	0	3	1.0	3.3	8.6
4	0	3	1.5	3.5	9.2
5	0	3	2.0	3.5	8.7
6	20	3	0	3.1	6.6
7	20	3	0.5	5.8	8.8
8	20	3	1.0	7.2	9.4
9	20	3	1.5	7.7	9.7
10	20	3	2.0	7.5	9

TABLE 5: Results of workability test (slump test).

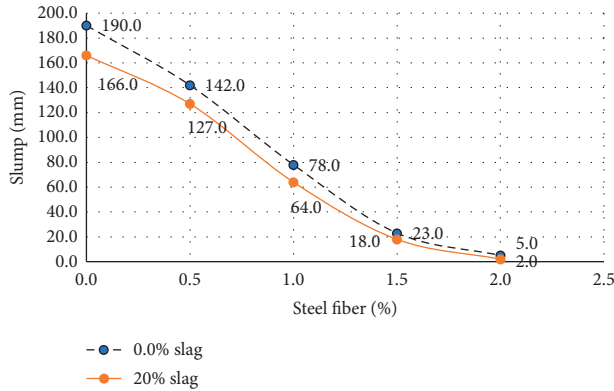| Mixture	Steel slag (% of mass of CM)	Superplasticizer (% of mass of cement)	Steel fibers (% of volume of concrete)	Slump value (mm)
1	0	3	0	190
2	0	3	0.5	142
3	0	3	1.0	78
4	0	3	1.5	24
5	0	3	2.0	5
6	20	3	0	166
7	20	3	0.5	127
8	20	3	1.0	64
9	20	3	1.5	18
10	20	3	2.0	2.0

FIGURE 2: Slump results at different fiber concentrations, with 0% and 20% slag.
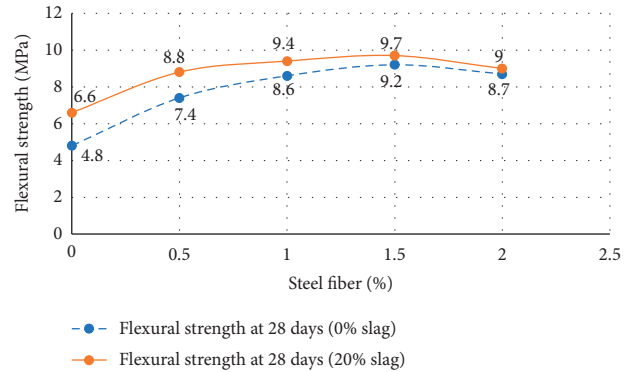

FIGURE 3: Results of flexural strength test with 0% and 20% slag at different concentrations of fibers.

For flexural strength, the results showed that using steel fibers only without adding steel slag led to an increase in the flexural strength. By increasing the concentration of the steel fibers, the flexural strength increased significantly until the concentration of fibers was up to the 1.0%, and after that, the increase in strength was insignificant at 1.5% steel fiber concentration; finally, the flexural strength began to decrease gradually when fibers more than 1.5% was used. The highest flexural strength was achieved using 1.5% steel fibers with value of 9.7 MPa, as shown in Figure 3.

The second stage of the study was to test the effect of using 20% steel slag as a supplementary material in addition to using the steel fibers in the concrete mixtures, simultaneously. The results showed that there was an increase in flexural strength for all mixtures (at all fiber concentrations) compared to concrete mixtures with fibers only. Using steel slag improved the flexural strength of the steel fiber reinforced concrete by 3.3–15.9%. The maximum increase in flexural strength was achieved at 0.5% steel fibers with 15.9%. As a result, using a concrete mixture with 20% steel slag and 1.5% steel fiber may lead to an increase in flexural strength by 50.5% compared to reference concrete mixture without slag and fibers. Moreover, using a concrete mixture with 20% steel slag and 1.0% steel fibers may lead to an increase in flexural strength by 48.9% compared to reference concrete mixture without slag and fibers.

The significant increase in flexural strength that can be obtained using steel fibers could be explained by the following:

(1) The improvement in concrete ductility due to the addition of steel fibers, and this is due to the behavior of a composite element of fiber concrete which prevents the brittle failure of fiber concrete element [27].

(2) The significant improvement in concrete toughness, which leads to an increase in flexural strength, and thus increasing the steel fiber fraction and values of aspect ratios leads to more toughness [28].

(3) Crack bridging action of steel fibers; since fibers can act as a "bridge" through cracks, this can lead to improving the cracking resistance of concrete, which is confining or preventing crack propagation and improving flexural strength [27].

(4) The significant increase in the strain and stress at peak (without variation in peak stress), which could increase the peak stress of concrete up to 39.17 percent, while the strain value can increase up to 657.14 percent [29].

The third stage of the study was to test the effect of using steel fibers and steel slag on the early flexural strength of concrete at 7 days. The results showed that flexural strength at 7 days for concrete mixtures without slag and fibers was 47% of flexural strength at 28 days for the same concrete mixture, whereas for concrete mixtures with steel fibers and steel slag, the flexural strength at 7 days was 66%–83.3% of the flexural strength at 28 days for the same mixtures, based on the concentration of fibers (0.5%, 1.0%, 1.5%, and 2.0%). In other words, using steel slag and steel fibers in concrete mixtures led to a significant increase in early flexural strength of the concrete compared to the reference mixture (without fibers and slag), as shown in Figure 4.

The significant increase in early flexural strength that could be obtained by using steel fibers is related to several interrelated factors. Flexural (bending) strength of concrete depends on resisting the internal tensile strength that is formed in concrete, and therefore, using steel fibers could lead to a higher resistance to internal tension since the steel is better than concrete in tension resistance; the resistance of steel to tension depends mainly on the length and mechanical properties of steel fibers rather than concrete age, since the concrete could achieve around 60% of the design strength just at 7 days [30]. Moreover, the main role of dispersed fibers is to control the opening and development of cracks that are formed due to internal tension by bridging the faces of cracks; the success of bridging generally depends on pull-out mechanisms. Pull-out strength depends on not only bond quality between fibers and matrix but also fiber shape properties. To improve pull-out resistance, mechanically deformed fibers are more effective than straight fibers [31].

Based on the results of slump and flexural strength tests, a concrete mixture with 20% steel slag and steel fibers between 1.0% and 1.5% could achieve the highest flexural
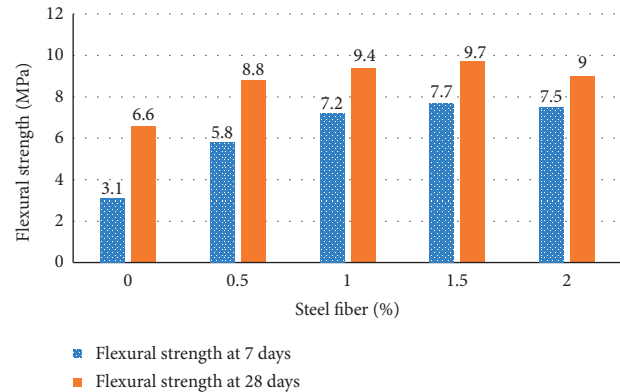

Figure 4: Results of flexural strength test at 7 and 28 days, with 20% slag at different concentrations of fibers.

strength with minimum acceptable workability; the achieved increase in flexural strength could be between 48.9% and 50.5% compared to normal concrete mixture without fibers and steel. Therefore, a higher performance and less thickness concrete pavement (rigid pavement) can be developed by achieving higher flexural strength [8]. More specifically, it was found that increasing the flexural strength of concrete from 3.45 to 5.5 MPa could reduce the required thickness by between 24% and 31% depending on other parameters affecting the thickness [32]. Thus, a reduction in pavement thickness by more than 30% could be achieved by using 20% steel slag and 1.5% steel fibers.

5. Conclusions

Flexural strength is one of the principle factors in rigid pavement design; therefore, it affects the performance and thickness of concrete pavement. In order to increase the flexural strength of concrete pavement, a concrete mixture was developed using steel fibers and steel slag (as a supplementary cementing material to replace a part of the cement). However, several studies investigated the effects of using steel fibers in concrete; the use of steel fibers in concrete faced some constraints because of workability problems. Furthermore, using steel fibers with high percentage could lead to a negative result on the flexural strength.

In this study, a new concrete mixture was developed using the steel fibers and steel slag with specific concentration. Using both materials led to a significant increase in flexural strength compared to mixtures with steel fibers only. By analyzing the results, the following findings were concluded:

(i) Using steel slag in concrete mixtures with steel fibers improved the flexural strength of the concrete by 3.3–15.9% compared to flexural strength achieved by adding steel fibers only

(ii) A concrete mixture with 20% steel slag and steel fibers between 1.0% and 1.5% could achieve the highest flexural strength with minimum acceptable workability; the achieved increase in flexural

strength could be between 48.9% and 50.5% compared to normal concrete mixture without fibers and steel

(iii) Using concrete mixtures with 20% slag and steel fiber concentration less than 1.5% could be suitable for pavement which complies with ACI standards for workability

(iv) Using steel fibers and steel slag with specific amounts leads to an increase in the early flexural strength (at 7 days); more specifically, the achieved early flexural strength could be increased by 66%–83.3% of the flexural strength at 28 days. In other words, the early flexural strength could be increased by 59.7% when 1.5% steel fibers and 20% steel slag were used, compared to reference concrete mixture without fibers and slag

(v) Using concrete mixture with 20% steel slag and steel fibers between 1.0% and 1.5% could reduce the required thickness of rigid pavement by more than 30%; therefore, a significant cost benefit could be achieved

(vi) Testing mixtures with higher percentage of steel fibers and slag simultaneously with changing the type and dosages of superplasticizer is highly recommended for any future work, since using the same type of superplasticizer will not lead to better results due to low workability and low flexural strength that are obtained when steel fibers more than 1.5% are used

Data Availability

The data used to support the findings of the study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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