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Compressive strength of cement-bound base layers containing ferrochromium slag

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Abstract: In this study, the compressive strength properties of flexible pavement's cement-bound base layers made with FeCr slag have been investigated. The physical and chemical properties of the materials (FeCr slag and cementitious binders) were determined. Cylinder-shaped slag specimens containing 2%, 4%, 6%, 8%, and 10% Portland cement (PC) and silica fume were then prepared and stored for 28 days in a humid room. Nondestructive testing was performed using ultrasonic pulse velocity (UPV), and then unconfined compressive strength (UCS) testing was applied to the samples. The results of both testing methods are discussed comparatively. The test results showed that FeCr slag stabilized with cementitious binders can potentially be used as a road base layer material, in similar applications to traditional cement stabilized materials. Slag+PC mixtures met the required compressive strength properties of standards at 4% and higher PC contents. In this research, a high correlation was found between UCS and UPV test results.

Key words: Unconfined compressive strength, ultrasonic pulse velocity, ferrochromium slag, flexible pavement, cement-bound base layers

1. Introduction

Ferrochromium (FeCr) slag is a by-product from the production of ferrochromium, which is an essential component in the stainless steel industry. The slag is an attractive construction material due to its excellent material properties, but disposal of FeCr slag is associated with environmental and ecological problems (Fallman, 2000; Lind et al., 2001). The physical properties of FeCr slag, such as freeze–thaw resistance, Los Angeles abrasion value, water absorption, and California bearing ratio (CBR) properties, have been extensively tested. FeCr slag has been found to be a promising road construction material (Zelic, 2005; Sütaş and Yılmaz, 2006).

The FeCr slag samples used in this study were provided by the Antalya Ferrochrome Plant, one of the largest producers of FeCr in Eurasia, located in southern Turkey. The current level of production of FeCr slag is about 45,000 t/year. In untreated conditions, the bulk density of the slag is around 1.8 t/m^3 and the volume generated is about 81000 m^3/year (Yılmaz, 2008). A relatively small percentage of FeCr slag finds applications, but the rest is held in dumps, and as the land disposal costs increase, new disposal options are needed.

An alternative way to use slag employed in many European countries is as an unbound granular material in road construction. However, because of concerns of leaching of heavy metals and subsequent effects on water quality, this alternative has sometimes not been preferred as the best option. Therefore, consideration has been given to using the slag as an aggregate in cement-bound pavement layers (Fallman, 2000). Cement-bound

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systems, and especially Portland cement (PC), have been used for immobilizing the soluble toxic elements. They provide chemical as well as physical immobilization potential for conditioning of toxic metals (Kindness at al., 1994; Conner, 1997).

This paper reports a laboratory study investigating the use of FeCr slag as an aggregate in cement-bound mixtures to be used in base layers of flexible pavements. In the laboratory, the compressive strength properties of slag samples were studied using destructive and nondestructive testing methods. The results of both methods are discussed comparatively.

In recent years, the potential use of FeCr slag as an aggregate in concrete or asphalt mixes has been investigated (Emery, 1982; Giesekke et al., 2000; Pioro and Pioro, 2004; Zelic, 2005; Niemelä and Kauppi, 2007). In this study, both destructive and nondestructive testing methods were applied and experimental data relationships were obtained for cement-bound FeCr slag mixture.

The traditional testing method to determine the compressive strength of cylindrically shaped specimens is the unconfined compressive test (ASTM D-1633; American Society for Testing and Materials, 2000). Although this kind of destructive testing method gives realistic results, it is both time-consuming and costly. It is also possible to analyze material properties by nondestructive testing methods. The methods of nondestructive testing were not developed for replacing the destructive testing methods entirely, but they came to be an alternative to the destructive testing methods as more practical, faster, and inexpensive methods (Erdoğan and Özer, 1996; Malhotra, 2004). In this study, in addition to the unconfined compressive strength (UCS) test, the ultrasonic pulse velocity (UPV) test has also been applied to the samples. The UPV test, a well-known nondestructive test, covers the determination of the pulse propagation velocity of compression waves in cement-bound samples. The pulse velocity "V" is related to the physical properties of a solid by an equation (Qasrawi, 2000; Turgut, 2004).

2. Materials

The materials used in the laboratory testing program are described below.

2.1. FeCr Slag

FeCr slag is a waste material obtained from the manufacture of FeCr. FeCr metal is produced in electric-arc furnaces by physicochemical process out of the oxide of chromium ore with coke as the reducing agent at a temperature of about 1500 °C. Both the liquids of the FeCr metal and of the slag flow out into ladles. After separation of the metal from the slag by means of their different specific gravities, the molten slag, slowly cooling in the air, forms a stable crystalline, dense product having excellent mechanical properties (Zelic, 2005). This kind of slag is called air-cooled electric-arc furnace (EAF) slag.

Most of the EAF slag (80%–90%) that is used in road construction is air-cooled crystallized slag (Ramirez, 1992; Lind, 2001). The physical properties of EAF slag after crushing and sieving offer advantages compared to other aggregates. Favorable properties are the lack of clay and organic ingredients in its composition, its rough and porous surface, and good adhesion as well as good abrasion resistance. On the other hand, the water absorption rate is somewhat high because of the porous nature of the slag. There are several potential fields of utilization of air-cooled EAF slag. It can be used as an aggregate in hot mix asphalt pavements, as an aggregate in concrete pavements, as a base or subbase material, as an embankment material, as railway ballast, and in snow and ice control (Ahmed, 1993; Dawson et al., 1995; Motz and Geiseler, 2001; Wu et al., 2007).

2.1.1. Physical properties of FeCr slag

The physical properties of the FeCr slag were determined and are illustrated in Table 1. According to the specifications of General Directorate of Turkish Highways (GDTH), the allowable material characteristics for base course layers are also given in Table 1. Water absorption of FeCr slag has been realized as partially high (2.3%). This is because of the porous nature of slag particles. The resistance of the slag aggregate to frost test was determined by the reference method TS EN 1367-1 (Turkish Standards Institution, 1999), by use of saturated magnesium sulfate solution. In TS EN 1367-1, samples are subjected to 5 cycles of the magnesium sulfate solution and subsequently dried at temperatures of 100–110 °C. The loss of mass after 5 cycles is measured (see Table 1). According to GDTH criteria, the physical properties of FeCr slag, as mentioned in Table 1, make it suitable as a pavement base material.

Table 1. Physical properties of FeCr slag.

Property	Unit	Standard	FeCr Slag	Specification (GDTH)
Water absorption (coarse aggregate)	%	TS EN 1097-6	2.32	≤ 2.5
Specific gravity	g/cm^3	TS EN 1097-6	3.01	-
Bulk density	g/cm^3	TS EN 1097-3	1.93	≥ 1.10
Los Angeles Abrasion Value	%	TS EN 1097-2	18.58	≤ 40
Freeze–thaw resistance ($MgSO_4$)	%	TS EN 1367-1	4.12	≤ 15
Liquid limit	-	TS 1900-1 (BS 1377)	Nonplastic	≤ 25
Plasticity	-	TS 1900-1 (BS 1377)	Nonplastic	≤ 6
CBR value	%	TS EN 13286-47	107	≥ 100*

*: Valid for untreated materials.

2.1.2. Chemical composition of FeCr slag

In order to determine the chemical composition, slag samples were ground to approximately 200 mesh, first in a jaw crusher and then in a ball mill crusher. Ground samples were screened through a No. 200 sieve. Samples passing through the No. 200 sieve were analyzed for main oxides using the ICP-ES method of the ACME Analytical Laboratory, Vancouver, Canada. Results of analysis are given in Figure 1. Figure 1a indicates FeCr slag and Figure 1b silica fume composition. The chemical composition of the FeCr slag includes 4 major elements: silicon, magnesium, aluminum, and calcium (Ca). Together with their oxides these components make up 90% of the slag.

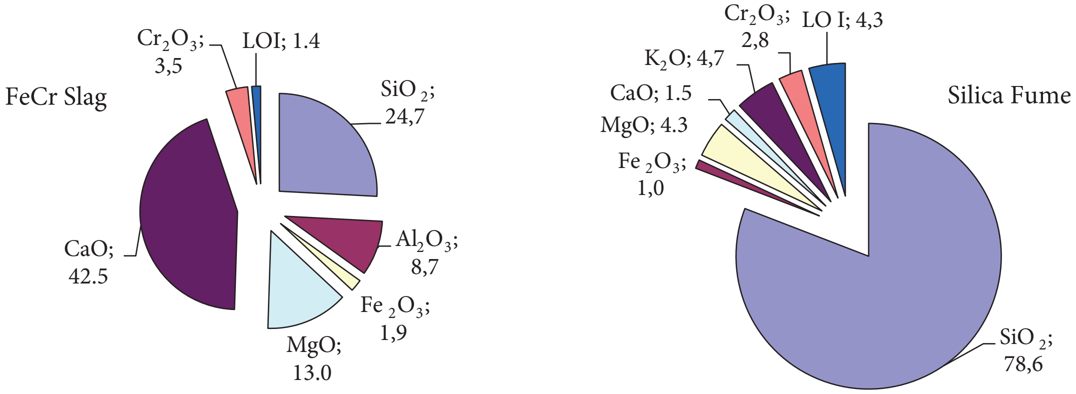

Figure 1. Chemical composition of FeCr slag and silica fume.

2.2. Silica fume and Portland cement

Silica fume (SF), containing a high degree (80%–90%) of amorphous SiO_2, is a gray-colored ash. It is an extremely fine material, with average diameters 100 times finer than those of Portland cement. Its surface area is approximately 20,000 m^2/kg and its bulk density is approximately 150–250 kg/m^3 (ACI Committee 226, 1987; Yeğinobalı, 1993). The SF used in this study was provided by the Antalya Ferrochrome Plant, Turkey, and it is used as a stabilizing agent in mixtures, like PC. The chemical composition of SF is given in Figure 1b. SF residue can be classified as a pozzolan. Initial work indicated that SF has a remarkably high pozzolanic activity. It can react with calcium hydroxide released by the hydration of cement and increase the strength of mortar significantly (Yeğinobalı, 1993; Erdoğan, 2003).

The ordinary PC (PC 42.5, CEM I 42.5 R) used in this study is up to the TS EN 197-1 standard (similar to European Standard EN 197-1; Turkish Standards Institute, 2002). It was obtained from the Isparta Göltaş Cement Factory, Turkey. The specific weight of PC is 3.10 g/cm^3 and the specific surface (Blaine value) is 3385 cm^2/g.

3. Experimental study

The particle size distribution of the FeCr slag is not suitable for use directly in pavement layers. Crushing and screening needs to be applied to oversized parts of the slag to realize the required grain size distribution shown in Figure 2. For this reason, oversized aggregates were crushed and screened in a 19-mm sieve. Grain size distribution curves used in this study are presented in Figure 2, where the well-graded and maximum particle size (D_{max}) is 19 mm in diameter.

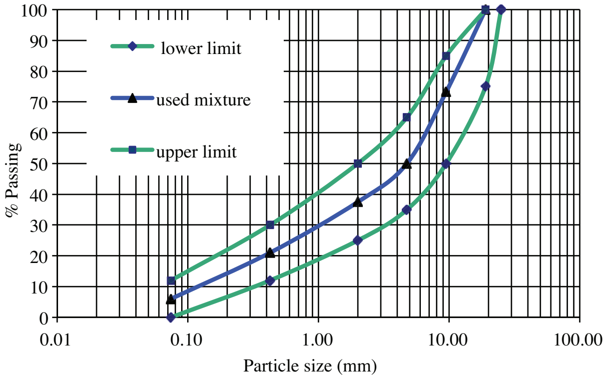

Figure 2. Grain size distribution curves used in the study.

3.1. Leaching tests

Some alternative aggregates may contain environmentally undesirable elements or compounds such as heavy metals. When they are used as aggregate in road construction, their water resource implications should be taken into account (Wu et al., 2007). To get information about the effect on the ground water and soil, it is of more interest to know the concentrations of these heavy metals that can be leached out.

The Synthetic Precipitation Leaching Procedure (SPLP) was used to evaluate the potential for leaching metals into ground and surface waters. This method provides a more realistic assessment of metal mobility under actual field conditions. The extraction fluid is intended to simulate precipitation. For this purpose, 100 g of slag sample (<2 mm fraction slag) was placed in a plastic bottle together with 2000 mL of leach solution (sulfuric/nitric acid solution). The pH of leach solutions was 4.2 and 5, respectively. The mixture was then agitated at 18 rpm for 24 h (Gericke, 1998) and filtered through a 0.45-μm glass fiber filter. Cr was analyzed by spectrophotometer (HACH DR/4000) using the diphenylcarbohydrazide method for Cr(VI) and alkaline hypobromite oxidation method for total Cr.

The SPLP test results are shown in Figure 3. Test results showed that only Cr content was significant as the heavy element in leaching extracts. Cr concentration in SPLP extracts obtained from crushed FeCr slag samples were 4 and 4.5 mg/L, meeting the US EPA (1994) limit of 5 mg/L for chromium.

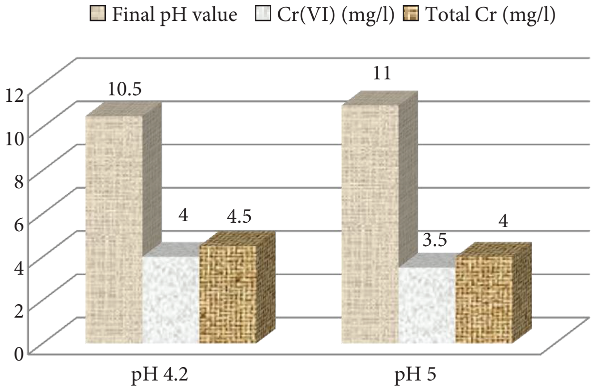

Figure 3. SPLP test results for pH 4.2 and pH 5.0.

3.2. Preparation of samples

Specimens were prepared as cylinders with length-to-diameter ratio of 2:1 (100 mm in diameter and 200 mm in height). Specimen diameter was chosen to be greater than 5 times the maximum particle size D_{max}. In order to achieve homogeneous samples, they were prepared by mixing 6 different fractions of slag aggregate, which was categorized in terms of particle size according to the gradation curve illustrated in Figure 2.

For sample preparation, first the dry materials were mixed for 2 min. The binder (PC and SF) was then added to the dry host material and mixed until visual inspection indicated uniform distribution. The percentages of the binding agents in the mixture were 2%, 4%, 6%, 8%, and 10% of the dry weight of the mixture. The required mass of distilled water, which was determined by the vibratory compaction method, was added and the sample was mixed again for another 2 min. Optimum moisture content of 7.5% and maximum dry density of 2.38 g/cm^3 were determined with vibratory compacting.

The mixture proportions of slag samples used in the study are given in Table 2. The wet mixture was placed in a cylindrical mold and compacted by vibrating table in 5 layers. All layers were vibrated under 2.5 kg of surcharge load until achieving maximum density. The split mold was stripped after 24 h and the samples were placed in a curing tank, which was kept in a humid room for 28 days. Three specimens were prepared for each mixture.

Samples were cured in a tank of minimum 90% relative humidity at a temperature of 22 ± 2 °C (see Figure 4). Samples were placed on a grid located 10 cm above the water level. The curing tank and specimens are illustrated in Figure 5. At the end of 28 days, the samples were weighed and dimensions were measured before testing.

Figure 4. Curing tank and specimens.

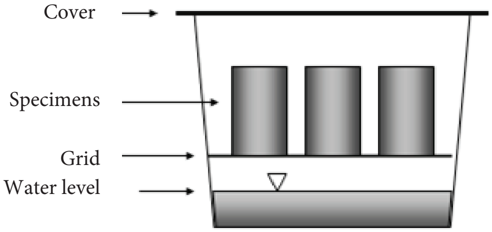

Figure 5. Storage of specimens for testing.

3.3. Testing methods

In order to determine the strength properties of specimens that represent the cement-bound base layers of pavements, UPV and UCS tests were carried out.

3.3.1. UPV test

There are several nondestructive testing methods to analyze the strength properties of materials, including the resonant frequency method, UPV method, and Schmidt hammer method. Some of them are not completely nondestructive and result in minor destruction in the surface of samples (Malhotra, 1993, 2004).

In this experimental work, before the execution of the destructive compressive test, the samples were tested using ultrasound for the determination of the velocity of the longitudinal ultrasonic waves within the samples. The velocity of the propagation of ultrasound pulses was measured by direct transmission using an ultrasound test device. The standard testing method is described in ASTM C-597 (American Society for Testing and Materials, 1998). The test device can produce and introduce a pulse into the specimen and it can accurately measure the time taken by the pulse to travel through the specimen. A pair of sensors is placed at opposite ends of the test sample. In one of the sensors, electronic pulses are generated, and the time for the pulses to propagate through the specimen is measured by the other sensor (Figure 6). Using the distance travelled, propagation velocity is calculated and, based on the velocity, the condition of the material is determined.

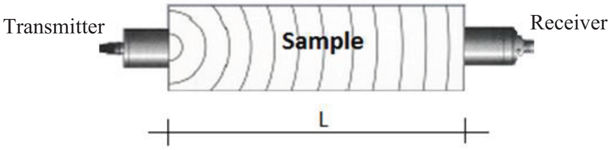

Figure 6. Schematic of ultrasound test application.

Pulse velocity V is related to the physical properties of a solid by Eq. (1):

$$V = L/T, \tag{1}$$

where V = pulse velocity (m/s), L = distance between transducers (m), and T = transit time (s).

A higher velocity usually means a better material quality (strength, durability, and dimensional stability). This technique is applicable both to field- and laboratory-prepared samples. Obtained results are not affected by the shape and size of the samples (Malhotra, 1993; Erdoğan, 2003).

3.3.2. UCS test

UCS is the most widely referenced property of cement-bound materials and is usually measured according to ASTM D-1633. It indicates the degree of reaction of the soil–cement–water mixture and the rate of hardening.

The UCS test was applied to slag-cement cylinders prepared with PC and SF binders. Specimens were tested by a compression testing machine with 50-t capacity. UCS was determined according to the ASTM D-1633 testing standard.

3.4. UCS test results

Compressive strength testing serves as a criterion for determining the minimum cement requirements for proportioning soil cement. According the American Concrete Institute (ACI Committee 230, 1998), the range of UCS for soil-cement is 2.76–6.89 MPa for sandy and gravelly soils (28th day soaked compressive strength). According to the GDTH, the range of 7th day UCS of soil-cement is 3.43–5.39 MPa.

The UCS test results of specimens prepared with PC and SF are plotted against binder content in Figure 7. The UCS of specimens increased along with the increasing binder content, as expected. Test results show that the UCS values of the tested materials were 3.2–13.01 MPa for PC stabilizing and 3.7–9.01 MPa for SF stabilizing. Specimens prepared with PC provided a higher UCS than did SF. Figure 7 shows that a logarithmic relationship can be used to approximate the relationship between compressive strength and cement content for cement contents of up to 10% and a curing period of 28 days.

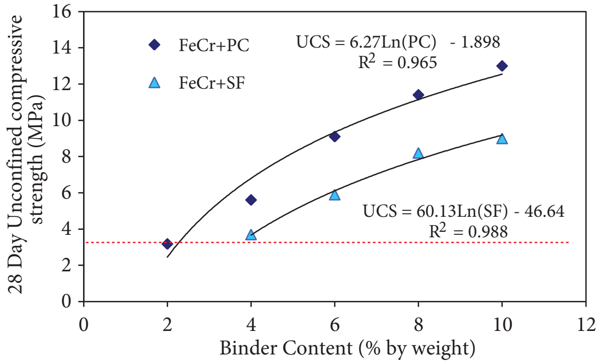

Figure 7. UCS results of slag samples after 28 days of curing (red line shows the minimum criterion for compressive strength).

Slag+PC mixtures meet the required compressive strength properties of standards at the 3% and higher PC contents. The strength developments of slag+SF samples and slag+PC samples have some differences. For SF cemented samples, strength increases rapidly until reaching an 8% SF content in the mixture, and then the strength development slows down with SF content. Above 8% SF contents, the workability of the mixture decreases because of the fineness of SF (for constant moisture-to-binder ratio). This phenomenon causes higher air voids and lower density in vibratory compacted specimens (see Table 2).

Table 2. Mixture proportions and sample densities.

Sample code	Stabilizer type		FeCr slag	Water*	Sample dry density
	PC (g)	SF (g)	(g)	(g)	kg/m^3
PC-2	85	-	4250	341	2415
PC-4	170	-	4250	363	2450
PC-6	255	-	4250	385	2505
PC-8	340	-	4250	407	2510
PC-10	425	-	4250	430	2520
SF-2	8.5	85	4250	343	-
SF-4	17	170	4250	368	2420
SF-6	25.5	255	4250	392	2425
SF-8	34	340	4250	416	2380
SF-10	42.5	425	4250	441	2285

*: Opt. moisture content of FeCr slag + water requirements of binder.

Slag+SF mixtures meet the required compressive strength properties of standards between 5% and 10% SF content. The sample that includes 2% SF was dispersed after being unmolded because of inadequate strength. Therefore, a strength test could not be applied to this specimen, or we assigned a value of “0”.

3.5. UPV test results and relation between UCS and UPV

The UPV values of specimens are plotted against binder content in Figure 8. The UPV of specimens increased along with increasing binder content. A logarithmic relationship can be used to approximate the relationship between pulse velocities and binder content. PC-added samples display higher UPV values than SF-added samples, as is shown in Figure 8. These UPV values approximately follow a similar pattern as the UCS values of the samples in Figure 7. The value of UPV increases as the specimen strength increases.

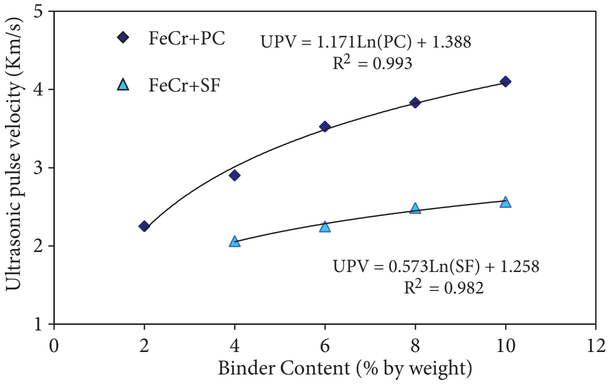

Figure 8. UPV results of slag samples after 28 days of curing.

In UPV testing, ultrasonic pulses move forward rapidly until meeting an air void. In denser samples, in a sample with less air voids, the ultrasonic pulse’s traveling time is shorter.

Some experimental data and the correlation between strength and pulse velocity of concrete were presented and proposed (Qasrawi, 2000; Rio et al., 2004). Some pulse velocity figures originally suggested by

Whitehurst for concrete with a density of approximately 2400 kg/m^3 were given as excellent (4500 m/s and above), good (3500–4500 m/s), doubtful (3000–3500 m/s), poor (2000–3000 m/s), and very poor (2000 m/s) (see Turgut, 2004).

Besides sample strength, some other effects could also affect pulse velocity. These include the age of the sample, moisture content, water-to-cement ratio, and type of aggregate. There is no unique relation between ultrasonic pulse velocity and strength. Nevertheless, experimental data relationships can be obtained from a given mixture. Regression analysis is a useful tool to evaluate the relationship between UCS and UPV test results.

In this study, an experimental relationship was determined between UCS and UPV test results for cement-bound FeCr slag. The best-fit curves obtained from the correlation of UCS and UPV are demonstrated in Figure 9.

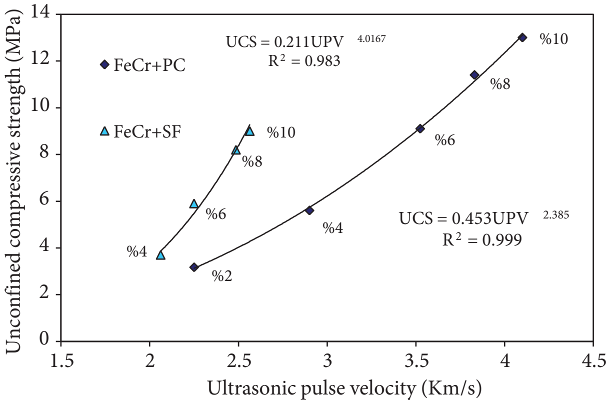

Figure 9. Relation between UCS and UPV test results.

Based on the findings of this research, the best-fitting curves have the following power-law equations.

For FeCr slag+PC:

$$UCS = 0.453(UPV)^{2.385} \tag{2}$$

For FeCr slag+SF:

$$UCS = 0.211(UPV)^{4.017} \tag{3}$$

The R^2 values of regression curves were found to be 0.98 and 0.99, which indicates a significant correlation. The standard error was found to be SE = 0.56 MPa for PC content and SE = 0.12 MPa for SF content. This approximate value for the standard error (S$_{yx}$) of the estimate tells us the accuracy to expect from our prediction [Eq. (2)].

$$S_{yx} = \sqrt{\frac{\sum (y-\bar{y})^2 - \frac{[\sum (x-\bar{x})(y-\bar{y})]^2}{\sum (x-\bar{x})^2}}{n-2}} \tag{4}$$

Ultrasonic measurements are relatively easy and time-saving processes. Strength properties calculated by ultrasonic measurements can be used in evaluation of the pavement materials' condition. This approach helps to predict the strength nondestructively.

4. Conclusions and recommendations

This research showed that the physical properties of FeCr slag have met the requirements of Turkish standards as an aggregate for pavement base layers. The properties of the FeCr slag, such as the lack of clay and organic ingredients in its composition, rough and porous surface, and good adhesion and abrasion resistance, offer advantages compared to other aggregates. Furthermore, the use of FeCr slag as an aggregate in pavement layers saves existing resources of natural aggregates.

This study verifies that FeCr slag+PC and FeCr slag+SF mixtures can be utilized as a road base layer material in specific mixture ratios. Slag mixtures prepared with PC and SF binders meet the required compressive strength properties of standards at 3% and higher PC content and at between 5% and 10% SF content, respectively. Using SF contents above 8% did not show any considerable strength increase. At higher SF contents, the workability of the mixture decreases because of the fineness of SF.

Additionally, it was observed that the UPV values approximately followed a similar pattern as the UCS values of the samples. There is no unique relation between UPV and strength. However, experimental data relationships can be obtained from a given mixture. In this work, a relationship was determined between UCS and UPV test results for cement-bound FeCr slag at lower binder ratios. The R^2 values of regression analysis were found to be 0.99 for PC- and SF-added mixtures. The UPV test is fast and easy to perform. Thus, strength properties calculated by ultrasonic measurements can be used in evaluation of the cement-bound pavement materials' condition.

For further studies, it is recommended to test field applications for verification of slag use in cement-bound layers of pavements. Grinding and sieving efforts of FeCr slag also have to be considered as of prime importance in the material's use as an aggregate.

Acknowledgment

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Nomenclature

UPV	Ultrasonic pulse velocity
UCS	Unconfined compressive strength
PC	Portland cement
SF	Silica fume
CBR	California bearing ratio
FeCr	Ferrochromium
EAF	Electric-arc furnace
GDTH	General Directorate of Turkish Highways
ICP-ES	Inductively coupled-plasma emission spectrometer
SPLP	Synthetic Precipitation Leaching Procedure
US EPA	United States Environmental Protection Agency
D_{max}	Maximum diameter
SE	Standard error

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