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Benefit–cost relationship of using concrete with blast furnace slag as road pavement

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Research Paper

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Benefit–cost relationship of using concrete with blast furnace slag as road pavement

In this study, the usability of concrete containing blast furnace slag (BFS; 15, 20, 25, 30 wt.%) as road pavement on soils with weak bearing strength and the corresponding benefit–cost relationship were investigated. The prepared concrete specimens were subjected to physical and mechanical tests following different curing times, and it was determined that the mechanical strength of the BFS-added specimens increased and peaked at the BFS content of 20 %. In addition, according to the AASHTO 1993 design method, it was determined that the thickness of the BFS-added concrete pavement decreased by 1.58 % to 3.38 % and the cost was reduced by 5.59 % to 10.30 %.

Key words:

road pavement, blast furnace slag, very weak bearing strength soil, concrete slab, AASHTO method

Prethodno priopćenje

Tacettin Geçkil, Mehmet Mahmut Tanyıldızı, Ceren Beyza İnce

Odnos koristi i troškova korištenja betona s udjelom zgure iz visoke peći kao cestovnoga kolnika

U ovome istraživanju ispitani su upotreba betona s udjelom zgure iz visoke peći (eng. blast furnace slag - BFS) u postotku od 15, 20, 25 i 30 % u odnosu na masu cementa, kao cestovnoga kolnika na tlima slabe nosivosti te odnos koristi i troškova u njegovoj upotrebi. Pripremljeni uzorci betona podvrgnuti su fizikalnim i mehaničkim ispitivanjima prateći njegovanje različitoga trajanja, čime je utvrđeno da se čvrstoća uzoraka kojima je dodan BFS povećala te da je bila najveća kod uzoraka s udjelom BFS-a od 20 %. Štoviše, prema metodi projektiranja AASHTO 1993, dokazano je da se debljina betonskoga kolnika kojemu je dodan BFS smanjila za 1,58 do 3,38 %, a da su se troškovi smanjili za 5,59 do 10,30 %.

Ključne riječi:

cestovni kolnik, beton s udjelom zgure iz visoke peći, tlo vrlo slabe nosivosti, betonska ploča, metoda projektiranja AASHTO

1. Introduction

To meet the needs emerging in recent years, the use of concretes newly developed with various properties, which eliminate various problems with their functional use, is becoming more and more widespread. Improving the properties of such concretes, which continue to be important building materials today, with various additives continues to be an important subject of research [1-3].

In parallel with technological developments, more advantageous building materials have been sought to improve concrete properties. In particular, to produce concrete with high compressive, splitting-tensile, and flexural strengths, other mechanical properties of concrete must be increased by adding pozzolan [4]. In addition to improving the properties of concrete, investigations have been conducted on how the strength and cost change with the use of pozzolans instead of cement, which is a binder, and it has been stated that significant strength gains are obtained by recycling BFS, a waste material, and using BFS-substituted concretes up to a certain level [5, 6]. Regarding these properties, a concrete road pavement that can meet the economic, superior quality, safety, and comfort criteria incorporating BFS has gained interest throughout the country. The purpose of this project is to calculate the concrete slab thickness in such a way that deformations do not occur while safely carrying the traffic that will pass over the pavement during the design life, and to determine the properties of the materials to be used in the pavement [7, 8]. In the research conducted on pozzolana-added concretes, it has been stated that concretes containing BFS require less water than concrete with Portland cement. The rubbed surface texture of the slag particles and the later onset of chemical reactions of the slag [9] increase the compressive strength of concrete due to the fact that BFS better fills the gaps in the aggregate-binding interface, the 7-day compressive strength of concretes containing slag partially replaced cement is lower than that of control specimens, the fact that this situation should be considered in concretes where early strength is required, 28 and 90-day compressive strengths of concretes containing 25 % slag are higher than the strengths of control specimens, BFS has slightly higher splitting-tensile and flexural strengths compared to Portland cement concretes with the same compressive strength [10] were identified as the reasons for this.

In other relative studies, the workability of slag-added concretes has been observed to increase because BFS has a lower surface roughness compared with clinker and due to its low specific gravity, more cement paste is obtained in volume. For the same workability, it was determined that the water/binder ratio of the mixture decreased with an increase in the amount of BFS in the concrete. Based on this, it has been determined that BFS has a positive effect on workability [11 ,12], and the 7-day compressive strength of concretes containing slag is lower than that of control specimens, regardless of the amount of slag partially used instead of cement and the water/binder ratio. It was understood that the compressive strengths of 28- and 90-day specimens tended to increase compared with the control specimens. In the case of equal cement content and equal water/cement ratios, slag cements resulted in relatively low concrete strength values at early ages and higher concrete strength values at late ages compared with normal Portland cements [13-15]. Further, the substitution of cement with BFS at 20 %–30 % was found to cause a slight decrease in the early-term strengths. However, with the development of the pozzolanic reaction, this difference was closed in 28-day strengths and increased compared with the control specimens [16, 17]. Slump, compressive, and splitting-tensile tests were performed on these specimens considering 0, 10, 20, and 30 wt. % BFS instead of cement. It was determined that as the amount of BFS increased, the workability of concrete mixtures increased, and as the BFS replacement rate in concrete increased, the compressive strengths increased up to 20 % at advanced ages and decreased at 30 % replacement rate [18].

It seems that most of the existing studies on BFS only aimed at improving the strength properties of concrete. However, concrete is not only used in structures such as buildings and bridges, but also in road construction. A multidisciplinary approach was avoided in these studies. For this reason, the use of improved concretes as road pavement under different traffic and soil conditions and its benefit–cost relationship have been left largely unaddressed until now.

In this study, unlike previous research, the usability of concretes containing 0, 15, 20, 25, and 30 wt. % BFS instead of cement in concrete pavements for soils with very weak bearing strength was investigated. Accordingly, workability, compression, flexural, and splitting-tensile and freeze-thaw tests were carried out on the concretes, and the usability of these concretes produced according to the test results in road concrete pavements was examined. In addition, with the help of the AASHTO 1993 design method, concrete pavement thicknesses were determined for pure and BFS-added concretes, current costs were calculated, and the usability of BFS in concrete pavements was evaluated.

2. Materials used in the research

2.1. Cement

The CEM I 42.5 R type Portland Cement (PC) produced by the Tracim Cimento San. ve Tic. A.S. in compliance with TS EN 197-1 [19] was employed in this study. The tap water of Tekirdag/Corlu city was used in the concrete mixture. The chemical and physical properties of CEM I 42.5 R cement are provided in Table 1.

2.2. Blast furnace slag (BFS)

BFS was procured from Karcimsa Ltd. Sti. and was used by replacing cement by weight within the scope of the study. The BFS specimen used is shown in Figure 1, its properties are detailed in Table 2.

Table 1. Chemical and physical properties of the CEM I 42,5 R cement

Chemical properties									
Component	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**Insoluble residue**	**Ignition loss**	**Free lime**
[%]	19.41	4.50	3.49	63.09	1.10	3.20	0.80	3.80	1.90
Physical properties									
Setting begin	155 [min]								
Setting last	235 [min]								
Volume constancy	1.00 [mm]								
Specific surface	3.720.00 [cm^2/g]								
Specific weight	3.08 [g/cm^3]								
Compressive strength									
2-day compressive strength	38.60 [%]								
7-day compressive strength	57.40 [%]								

Table 2. Chemical and physical properties of BFS

Chemical properties												
Component	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**Na_2O**	**Mn_2O_3**	**K_2O**	**TiO_2**	**S**	**Cl**
[%]	34.01	11.95	1.18	31.65	8.51	0.61	0.52	3.58	0.71	1.32	0.47	0.014
Physical properties												
Moisture content	0.10 [%]											
Specific weight	2.90 [g/cm^3]											
Specific surface	4.417 [cm^2/g]											
45-mm sieve balance	0.010 [%]											
90-mm sieve balance	0 [%]											

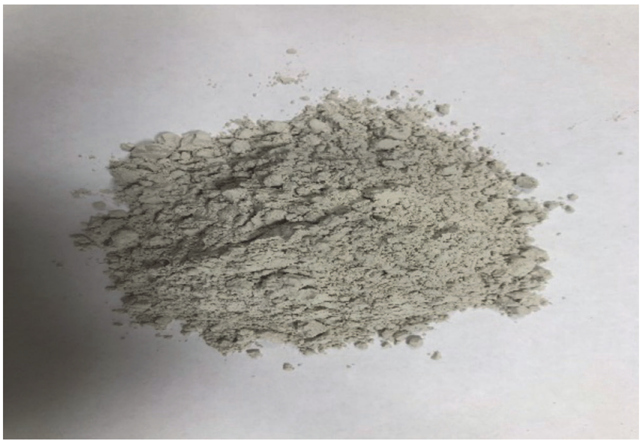

Figure 1. Blast furnace slag (BFS) specimen used in the study

2.3. Aggregate

Aggregates used in the study were supplied by Dalbay Tas Imalatı San. ve Tic. Ltd. Sti. (Kırklareli Central District Kapaklı Village). Aggregates are divided into three different material classes: 0–5 mm (crushed sand), 5–11 mm (crushed stone), and 11–22 mm (crushed stone). In the production of concrete with the largest grain size of 22 mm, these aggregates were used at ratios of 22 %, 38 %, and 40 %, respectively. The physical and chemical properties of the aggregates are presented in Table 3 and the grain size curve of the mixture is displayed in Figure 2 according to the TS EN 933-1 standard limits [20].

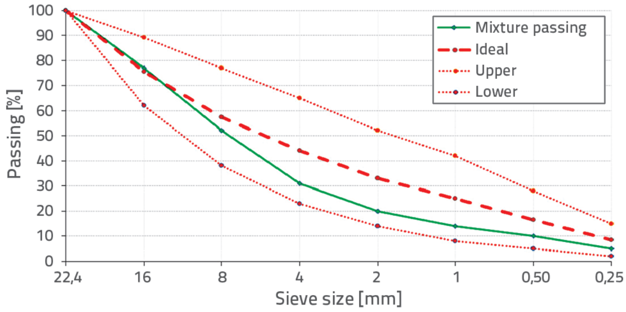

Figure 2. Grain size curve of the aggregate mixture

Table 3. Physical and chemical properties of the aggregate

Property	0 – 5 [mm]	5 – 11 [mm]	11 – 22 [mm]	Standard
Water absorption [%]	1.40	0.70	0.40	≤ 2.5 (TS EN 1097- 6) [21]
Specific weight[kg/m³]	2.77	2.79	2.80	-
Resistance to fragmentation of coarse aggregates (micro-Deval abrasion resistance) [%]	-	18.00	18.00	≤ 25 (TS EN 1097- 2) [22]
Volume stability-drying shrinkage [%]	0.022	0.022	0.022	≤ 0.075 (TS EN 1367-4) [23]
Alkali silica reaction [%]	0.030	0.030	0.030	≤ 0.10 (CANADA. CSA23.2 25A [24]

2.4. Chemical additive

To increase the workability of the fresh concrete and ensure a final high performance, a superplasticizer at the ratio of 1.34 % of the binder was incorporated into the concrete mixture with the water/cement ratio of 0.40. According to the TS 781 ISO 758 standard [25], the specific gravity of chemical additives at 20 °C should be between 1.08 g/cm³ and 1.12 g/cm³. The specific gravity of the superplasticizer used was determined as 1.11 g/cm³ at 20 °C.

3. Methods used in the research

3.1. Experimental method

3.1.1. Preparation of concrete mixtures

CEM I 42.5 R-type cement, aggregates containing particles of 0–5, 5–11, and 11–22 mm, tap water, and BFS were used in the concrete specimens produced in this study. The water/cement ratio was considered as 0.40 in the concretes produced, and BFS was added at 0, 15, 20, 25, and 30 wt. %. Five concrete specimens were designed for the experiments. The produced control specimens and mixtures were coded as follows and the mixing ratios are given in Table 4.
- Cement (K-C): Control specimen with cement as the binder
- Cement+15wt. %BFS (C15B): 15 wt. % BFS substituting for the binding cement
- Cement+20wt. %BFS (C20B): 20 wt. % BFS substituting for the binding cement
- Cement+25wt. %BFS (C25B): 25 wt. % BFS substituting for the binding cement
- Cement+30wt. %BFS (C30B): 30 wt. % BFS substituting for the binder cement

After the components that make up the specimens were weighed based on the ratios in Table 4, the aggregates were placed in order from the largest to the smallest in grain size in the mixer of 80-dm³ capacity, then cement and BFS were added. The formed content was then mixed for approximately 2 min to obtain a dry mixture. Afterwards, 90 % of the water was added to the mixer and the mixing process was continued for 3 min. Then, a plasticizer was added with the remaining 10 % water and the mixing process was continued for another 5 min. The process was completed by mixing the material for the total of 10 min. It was seen that sufficient mixing time was provided to ensure workability, and to obtain the desired efficiency from the superplasticizer in mixtures with low water/binder ratio and high additive dosage. The specimens remained covered for 24 h in the laboratory environment to prevent the evaporation of the mixing water. After the set specimens were removed from the moulds, they were cured in a water-filled curing pool at 23±2 °C. The specimens were kept in the curing pool for 7, 28, and 90 days. All specimens removed from the curing pool were rendered saturated surface dry (SSD) in the laboratory environment. Compressive, flexural, and splitting-tensile strength tests were carried out on the SSD specimens. Prepared and cured concrete specimens are displayed in Figure 3.

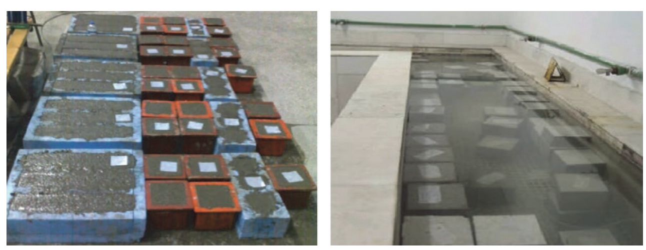

Figure 3. Prepared and cured concrete specimens

Table 4. Mixing ratios

Mixture code	Cement	BFS	Agregate [kg/m³]			Water [kg/m³]	Superplasticizer [kg/m³]	Water/binder [%]
			0 – 5 [mm]	5 – 11 [mm]	11 – 22 mm			
(K-C)	450	0	410	709	746	180	6	0.4
(C15B)	382.50	67.50	409	707	744			
(C20B)	360	90	409	707	744			
(C25B)	337.50	112.50	409	706	743			
(C30B)	315	135	409	706	743			

3.1.2. Workability and fluidity properties of concrete

The slump test was performed on the produced specimens to gain information about the consistency and workability of fresh concrete according to the TS EN 12350-2 standard [26] (Figure 4).

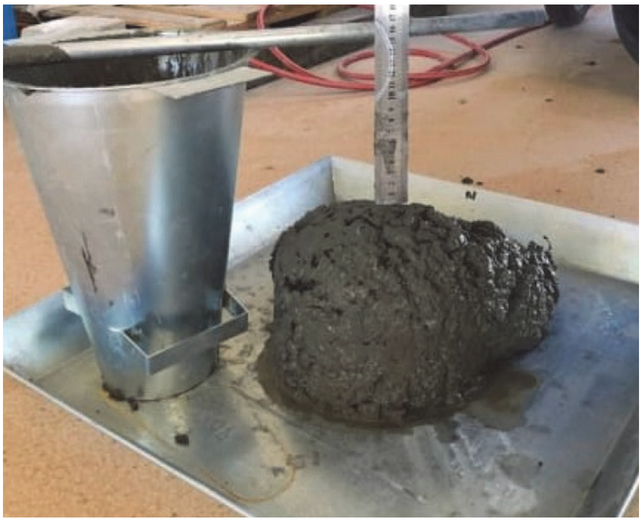

Figure 4. Application of slump test

In the slump test, after the concrete was filled to the level of one third of the slump cone, it was spuded 25 times and filled to the top surface of the cone in three steps. After the upper surface was smoothed with a trowel, the cone was lifted in the vertical direction without allowing shaking, and how much the cone slumped under the weight of the concrete was determined.

3.1.3. Compressive strength properties of concrete

Control and cement-substituted mixtures were placed in moulds and kept in the laboratory for 24 h. Subsequently, the cured specimens were taken out of the moulds and remained in the curing pool at 23±2 °C for 7, 28, and 90 days. All specimens were removed from the pool at the end of the curing period and remained in the laboratory for a minimum of 3 h to realize SSD. Three cubic specimens of 150 mm x 150 mm x 150 mm in SSD form were tested. The tests were carried out using a press with the pressure capacity of 300 t and loading speed of 0.50 MPa/s, as depicted in Figure 5.

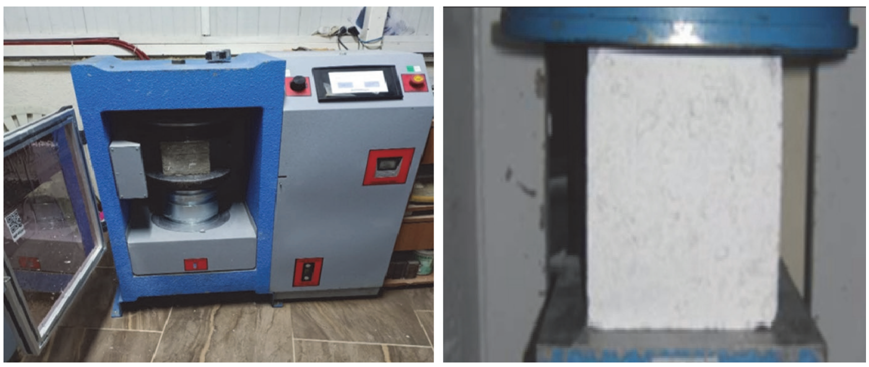

Figure 5. Compressive strength test of specimens

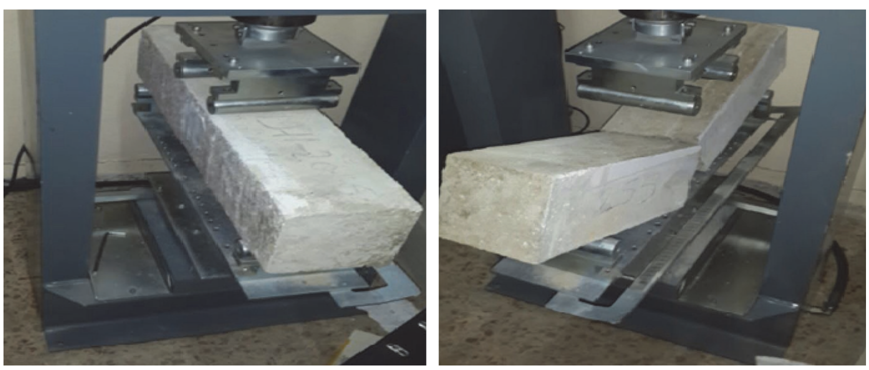

Figure 6. Flexural strength testing of specimens

3.1.4. Flexural strength properties of concrete

The flexural strengths of the prepared concrete specimens were determined via a four-point flexural test performed on 150 mm x 150 mm x 525 mm beam specimens that were cured for 7, 28, and 90 days. The experiment was performed by applying the loading speed of 0.05 MPa/s using the press with the bending capacity of 20 t. The flexural strength testing of the control and BFS-added specimens is depicted in Figure 6.

3.1.5. Splitting tensile strength properties of concrete

Three-cylinder specimens of Ø150 mm ´ 300 mm were tested to determine the splitting-tensile strength of the control and BFS mixtures at the end of the 7-, 28-, and, 90-day curing periods. The experiment was conducted using a press with the pressure capacity of 300 t and loading speed of 1.6 kN/s. The splitting tensile testing of the control and BFS-added specimens is presented in Figure 7.

3.1.6. Freeze-thaw resistance properties of concrete

An experiment was performed to determine the resistance of BFS-added concrete pavement considering occurrence of freeze-thaw periods during its service life. The control and BFS-added concrete specimens were subjected to

Figure 7. Splitting tensile strength testing of specimens

Table 5. Freeze-thaw resistance categories

Category	Mass loss (28 days)
FT0 (Freeze-thaw free places)	-
FT1 (Freeze-thaw places)	Average < 1.0 [kg/m²]
FT2 (Places with freeze-thaw and where defrosting agents are used)	Average < 0.5 [kg/m²]

freeze-thaw resistance tests based on the CDF test method according to the TSE CEN/TS 12390-9 standard. According to Table 5, specified regarding the TCK Highways Concrete Road Pavements Technical Specification [27] in Turkey, the freeze-thaw resistance category was determined as FT2, based on the climatic conditions of the region where the study was conducted.

Before the experiment, after the fresh concrete was placed in the moulds, the moulds were protected against drying for one day at 20±2 °C. The specimens were then removed from the moulds after 24±2 h and placed in a curing pool filled with tap water at the temperature of 20±2 °C. The specimens were removed from the curing pool on the 7th day and placed in the curing chamber at 20±2 °C and 65±5 % relative humidity for 21 days until the experiments began. Specimens cured for 28 days were saturated with test liquid (97 % tap water by mass and 3 % NaCl) as a capillary for 7 days, and the experiment was started on the 35th day. The specimens produced were evaluated by measuring the mass removed by flaking at the end of 28 freeze-thaw cycles, with 4 h of freezing at -20 °C and 4 h of thawing at +20 °C. Flaking fragments were separated from the specimen, collected, and weighed. Then, the mass loss values of the specimens were determined in g/mm² using Eq. (1).

$$m_n = (\mu_s/A)\cdot 10^6 \tag{1}$$

where:

m_n - the CDF weight loss [g/mm²]

μ_s - the amount of specimen breaking in *n* cycles [g]

A - the surface area of the specimen exposed to the freeze-thaw effect [mm²].

3.2. Design method

The aim in highway rigid pavement design is to determine the road pavement layer thicknesses as well as the material properties that will form these layers to be able to carry the traffic that will recur during the projected design life at a safe level without being exposed to cracks and deformations. As the AASHTO 1993 method has been used for rigid and flexible pavement road design in Turkey for years, this design method was considered as the basis in the study. In this context, the AASHTO 1993 equation for the performance of the concrete pavement, obtained by considering the effect of the 8.2-t standard equivalent single-axle load repetition number ($W_{8,2}$) on the performance of the pavement, is given in Eq. (2). The concrete pavement thickness (d) can also be calculated from Eq. (2) [28]:

$$\begin{aligned}\mathrm{Log}_{10}W_{8,2} = {} & Z_R\cdot S_0+7{,}35\cdot\log_{10}(d+1)-0{,}06+[\log_{10}[\Delta PSI/(4{,}5-1{,}5)]/\\ & [1+(1{,}624\cdot 10^7)/(d+1)^{8{,}46}]+(4{,}22-0{,}32\cdot p_t)\\ & \cdot\log_{10}[(S_c'\cdot C_d{}^*(d^{0{,}75}-1{,}132))/(215{,}63\cdot J\cdot d^{0{,}75}\\ & \cdot(18{,}42/(E_c/k^{0{,}25}))]\end{aligned} \tag{2}$$

where:

$W_{8,2}$ - Total number of standard axle load repetitions (8.2 t)

Z_R - Standard normal deviation

S_o - Total standard deviation

d - Plate thickness of pavement (in inchs, 1 in = 0,0254 m)

ΔPSI - Difference between the initial design service capability (p_o) and the final service capability index (p_t)

S_c' - Rupture module for concrete (psi) (6,8950 × 10³ Pa)

J - Load transfer coefficient

C_d - Road drainage coefficient

E_c - Elasticity module for concrete (psi) (6,8950 × 10³ Pa)

k - Base reaction module (pci) (27679,9 kg/m³).

3.2.1. Service capability (performance benchmark)

The service capability value of the pavement, which is accepted as a performance criterion in road engineering, was evaluated in the range of 0 to 5. Zero (0) indicates the lowest and five (5) the highest performance criteria grades. The initial performance criterion index (p_o) is shown as the final performance criterion index (p_t), and the p_o value decreases over time to an acceptable p_t value with the effects of increasing traffic loads and different environmental conditions. According to the AASHTO 1993 method, the p_o value was determined as 4.5 for rigid pavements [7]. p_0 = 4.5 and p_t = 2.5 from Table 6 were selected for the calculations completed within the scope of the study.

Table 6. Final service capability values

Road class	p_t
Highway and state road	2.5
Provincial road	2.0

3.2.2. Reliability

Reliability is expressed as the work of eliminating the malfunctions that may occur if the pavement resists traffic loads with a minimum resistance. The reliability level was selected from Table 7 [7].

Table 7. Recommended reliability levels

Road class	R [%]
Highway and state road	80 – 99.9
Provincial road	75 – 95
Collector road	75 – 95
Secondary and local road	50 – 80

The recommended values in the designs to be made for our country are expected to be 95 % for state roads and highways, and 85 % for provincial roads. Depending on the degree of reliability (R), the standard deviation (Z_R) of reliability was selected from Table 8 [7].

Table 8. Recommended reliability levels

Road class	Specification reliability value, R [%]	Standard normal deviation, Z_R
Highway	95	-1.645
State	85	-1.037
Provincial	70	-0.524

In the calculations made within the scope of the study, the R value for highways and state roads was chosen as 95 % from Table 9 and the Z_R value was chosen as -1,645 depending on the selected R value. It is recommended that the total standard deviation (S_o) be taken as 0.35 for rigid pavements [7].

3.2.3. Subgrade effective reaction module (k)

The effective reaction modulus (k) taken for the subgrade is also called the effective bearing coefficient in concrete (rigid) pavements. It is necessary to determine the k value, before concrete or rigid slab thickness calculations, using Eq. (3) [6].

$$k = P/Y \quad (3)$$

where:
P - the load to the subgrad (psi ili kg/cm²)
Y - the slump deformation (inches or cm)
k - the bearing coefficient-effective reaction modulus (psi/inch or kg/cm²/cm). The k value may vary depending on the bearing capacity, density, moisture content, and type of soil. Typical values for k are provided in Table 9 [28].

Table 9. Subgrade reaction module values

Ground condition	k [pci]
Very good (crushed stone)	≥ 550
Good (gravel)	400 – 550
Medium (sand and clay gravel)	250 – 350
Weak (Silt ve silty clay)	150 – 250
Very weak (plastic clay)	≤ 150

3.2.4. Elasticity module and rupture module of Portland cement concrete

The j daily elasticity module (E_{cj}) of concrete is determined using Eq. (4) according to the TS EN 12390-13 standard.

$$E_{cj} = 3250\sqrt{f_{ckj}} + 14.000 \text{ [MPa]} \quad (4)$$

where:
E_{cj} - the j daily modulus of elasticity (MPa) of concrete,
f_{ckj} - the j daily characteristic cylinder compressive strength of concrete (MPa, j = 28 days).

In the AASHTO design guide, the modulus of elasticity (E_c) values according to concrete classes are calculated from Eq. (5).

$$E_c = 6750 \cdot S'_c \quad (5)$$

where:
S'_c - the approximate modulus of rupture (6.8950 · 10³ Pa)
E_c - the modulus of elasticity (psi) of concrete with Portland cemen (6.8950 · 10³ Pa).

Flexural strength and rupture modulus (S'_c) are defined as 'the highest flexural strength reached by a concrete beam during fracture'. Flexural strength is calculated by breaking a concrete

Table 10. Drainage coefficient recommended for concrete pavement (C_d)

Drainage quality	Free water discharge time	Percentage of time the pavement is exposed to water content near saturation [%]			
		< 1	1 – 5	5 – 25	> 25
Very good	1 hour	1.25 – 1.20	1.20 – 1.15	1.15 – 1.10	1.10
Good	1 day	1.20 – 1.15	1.15 – 1.10	1.10 – 1.00	1.00
Medium	1 week	1.15 – 1.10	1.10 – 1.00	1.00 – 0.90	0.90
Bad	1 month	1.10 – 1.00	1.00 – 0.90	0.90 – 0.80	0.80
Too bad	Water cannot ve drained	1.00 – 0.90	0.90 – 0.80	0.80 – 0.70	0.70

beam of a certain size under mid-point or three-point loading after 28 days of curing [7].
Rupture modules, or flexural strengths, are calculated under these loads via Eq. (6) for one-third point loading and Eq. (7) for mid-point loading.

$$S'_c = (P \cdot L)/(b \cdot h^2) \tag{6}$$

$$S'_c = (3 \cdot P \cdot L)/(2 \cdot b \cdot h^2) \tag{7}$$

where:
S'_c - the shear modulus or flexural strength
b - the beam width
h - he beam height
P - the applied load
L - the length.

3.2.5. Drainage

The recommended values of the drainage coefficient (C_d) for concrete pavements are given in Table 10 [31]. In this study, the C_d value was taken as 1 for calculations.

3.2.6. Load transfer coefficient (J)

The load transfer coefficient J, which expresses the load transfer capability of the concrete pavement at the joints, is considered in the design of the concrete pavement. Load transfer coefficients according to the design conditions are presented in Table 11 [28]. In this study, J was assumed to be 2.7 for all calculations.

4. Research results

4.1. Experimental results

4.1.1. Slump test results

The BFS ratio–slump relationship of the control and BFS-containing concrete specimens is depicted in Figure 8.
Figure 8 shows that BFS has a positive effect on the workability of concrete with an increase in the ratio of BFS-substituted cement in concrete mixtures.

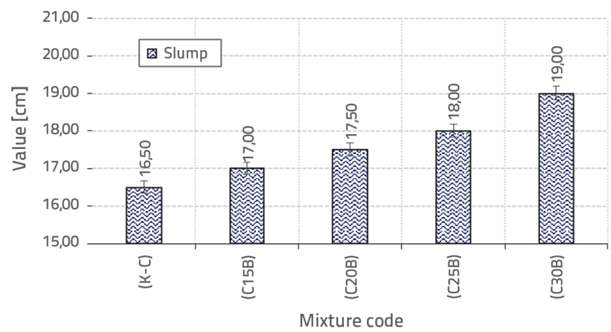

Figure 8. Change in slump values and BFS ratio

The use of BFS improves the workability of fresh concrete to a certain extent compared with control specimens and brings it to the S4 consistency class. In the literature, concretes have been produced using BFS and CEM I 42.5 cement, the amount of cement was kept constant and BFS was added at certain ratios (17 %, 33 %, and 50 %), and the effect of BFS on the properties of fresh and hardened concrete were investigated. Accordingly,

Table 11. Recommended load transfer coefficients

Banket (Berm)	Asphalt pavement		Concrete pavement	
Load transfer	**Have**	**None**	**Have**	**None**
Pavement type				
Reinforced / nonreinforced joint Continuously reinforced concrete	3.2 2.9 – 3.2	3.8 – 4.4 –	2.5 – 3.1 2.3 – 2.9	3.6 – 4.2 –

concrete specimens containing BFS at the ratios of 17 %, 33 %, and 50 % exhibit increased workability in fresh concrete [29, 30]. Moreover, in previous studies, it has been stated that this result is due to the fact that BFS particles have a smooth and glassy surface texture that is less permeable to water [31, 32].

4.1.2. Compressive strength test results

The variation in the compressive strength of the specimens with the additive ratio is displayed in Figure 9. As seen in Figure 9, the compressive strength of the specimens subjected to 7 days of curing time with BFS substitution decreased, while those of the 28- and 90-day specimens increased compared with the control specimens produced only with cement (K-C). This increase reached the maximum value in the C20B specimen, after which, the amount of increase reduced. Considering the 28-day curing period of the concrete, it was determined that the increase in compressive strength occurred at the rates of 9.97 %, 14.30 %, 5.89 % and 4.18 %, respectively, in 15, 20, 25, and 30 wt. % BFS-substituted concrete specimens compared with the reference control specimens.

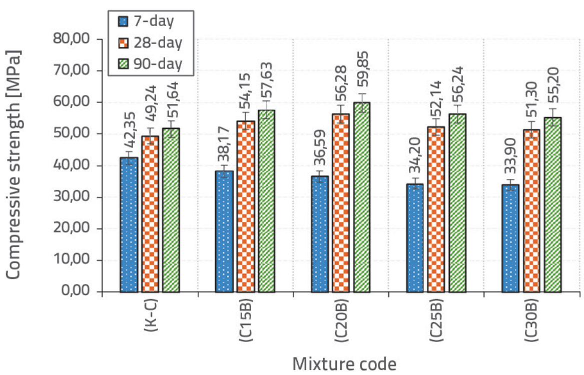

Figure 9. 7-, 28- and 90-day compressive strength results of control and BFS-added specimens

Considering previous works, with the use of 10, 20, and 30 wt. % BFS as a substitute for concrete, the 28-day compressive strength of concrete increased by 9 %, 8.5 %, and 6.2 %, respectively, compared with the control specimens [33]. Thus, the obtained results are compatible with the literature. However, the compressive strengths of the 90-day cured specimens increased by 12.47 %, 15.90 %, 8.90 %, and 6.93 %, respectively, compared with the control specimens. Considering these increases, the compressive strength of the specimens continued to increase with advancing curing time. According to the TCK Concrete Road Pavement Technical Specification [27], the design is based on the 28-day strength results of the concrete, and minimum C30/37 MPa is recommended as the strength class.

The compressive strength of the 28-day specimens was compared with C30/37 MPa within the scope of the study and the results are shown in Figure 10.

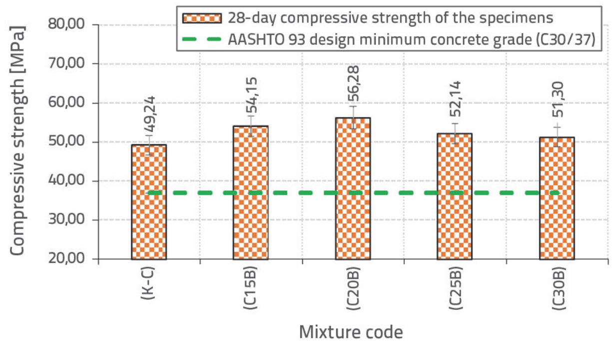

Figure 10. 28-day compressive strength design criteria of specimens

From Figure 10, at the end of the 28-day compressive strength, all specimens met the minimum characteristic compressive strength (C30/37) requirement according to the TCK Concrete Road Pavements Technical Specification.

4.1.3. Flexural strength test results

The variation in the flexural strengths of the control and BFS-added specimens with varying additive ratio is presented in Figure 11. As can be seen in Figure 11, the flexural strengths of all 7-, 28-, and 90-day specimens prepared with BFS additives increased compared with the control specimen produced with only cement (K-C). This increase reached the maximum value in the C20B specimen, after which the amount of increase decreased. Considering the 28-day curing period of the concrete, increases in flexural strength of 3.40 %, 6.42 %, 5.58 %, and 4.58 %, respectively, were determined in the 15, 20, 25, and 30 wt. % BFS-substituted concrete compared with the reference control specimens.

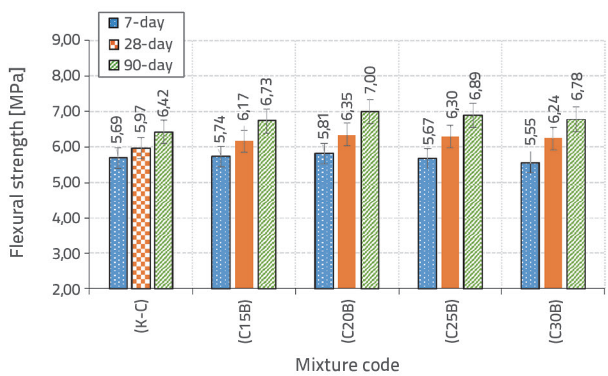

Figure 11. 7-, 28- and 90-day flexural strength graph of control and BFS added specimens

In previous works, the flexural strength of the mixtures prepared with BFS additive at different ratios instead of concrete was found to increase, by 1.08 % for 10 wt. % BFS additive [34]. However, according to the results of this study, the increase was higher. Further, the flexural strengths of the 90-day cured specimens increased by 4.82 %, 9.03 %, 7.32 %, and 5.61 %, respectively, compared with the control specimens. Considering these increases, the flexural strength of the specimens continued to increase with the extension of the curing time.

According to the TCK Concrete Road Pavements Technical Specification [27], the 28-day flexural strength should be greater than 4.50 N/mm^2. Within the scope of the study, the flexural strengths of the 28-day specimens were compared and the results are shown in Figure 12.

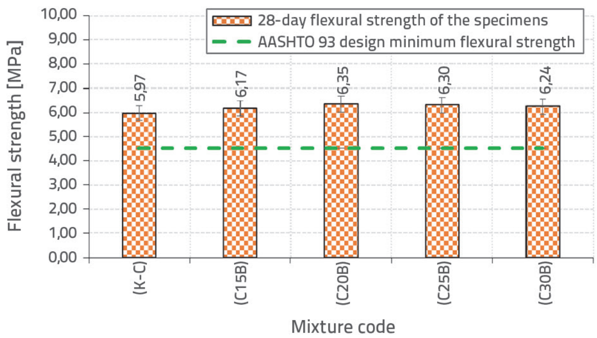

Figure 12. 28-day flexural strength design criteria of specimens

Figure 12 shows that at the end of the 28 days, all specimens met the minimum characteristic flexural strength (4.50 N/mm^2) required according to the TCK Concrete Road Pavements Technical Specification.

4.1.4. Splitting-tensile strength test results

The variation in the splitting tensile strengths of the control and BFS-added specimens regarding the additive ratio is depicted in Figure 13.

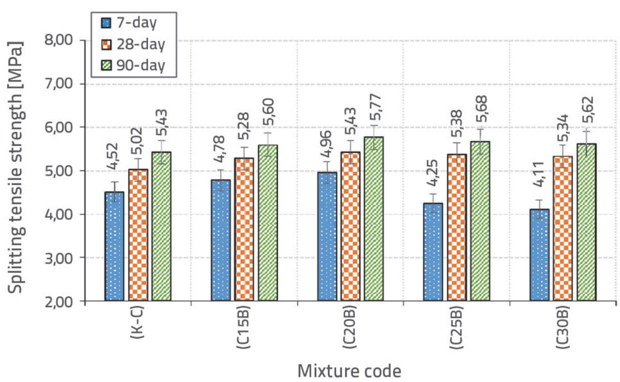

Figure 13. 7-, 28-, and 90-day splitting-tensile strength results of control and BFS-added specimens

From Figure 13, there was an increase in strength of the 7-day concrete specimens up to the C20B specimen, and a decrease in that of the C25B and C30B specimens after this value compared with the control specimens. It was determined that the splitting-tensile strength of specimens subjected to 28- and 90-day curing increased compared with the control specimens, and the maximum strength occurred in specimen C20B. The 28-day splitting-tensile strengths increased by 5.18 %, 8.17 %, 7.17 %, and 6.37 %, respectively, compared with the control specimens. In previous studies, when CEM I 42.5 R-type cement was considered, the splitting-tensile strength of the slag increased by 1.26 % when the 28-day splitting-tensile strength was reduced by 30 % and BFS was added [35]. However, the splitting-tensile strength of the 90-day cured specimens increased by 3.13 %, 6.26 %, 4.60 %, and 3.50 %, respectively, compared with the control specimens. Considering these increases, the splitting-tensile strength of the specimens continued to increase with the extension of the curing time.

According to the TCK Concrete Road Pavements Technical Specification [27], the splitting-tensile strength for 28-day cure specimens should be greater than 3.30 N/mm^2. Within the scope of the study, the splitting-tensile strengths of the 28-day specimens were compared and the results are shown in Figure 14.

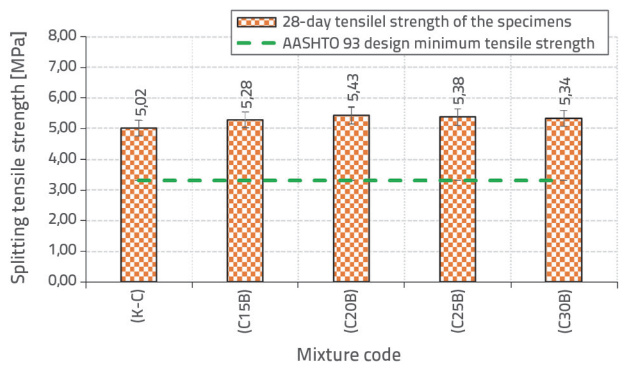

Figure 14. 28-day splitting-tensile strength design criteria of specimens

4.1.5. Freeze-thaw resistance test results

The mass losses obtained as a result of the experiments performed on cubic specimens (150 mm) are displayed in Figure 15.

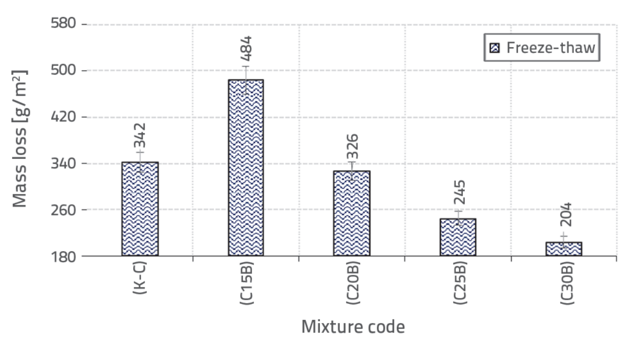

Figure 15. Freeze-thaw test results of the specimens

Figure 15 shows that the requirement for the mass loss resulting from 28 cycles to be less than 0.50 kg/m^2 in accordance with the TCK Concrete Roads Technical Specification was met. However, it is seen that the highest loss among the specimens occurred in those containing 15wt. %BFS (C15B), after which, compared with the control specimen (K-C), the mass losses for the C20B, C25B, and C30B specimens decreased by 4.68 %, 28.36 %, and 40.35 %, respectively; thus, their frost resistance increased. This is considered to be due to the fact that the internal stress in the concrete as a result of freezing is lower as the specimens with BFS additives are more porous. However, in previous studies, it was determined that the highest weight loss was achieved for 10 wt. % BFS, beyond which, a significant increase in strength (decrease in mass loss compared with the control specimens) occurred [36].

4.2. Design findings

4.2.1. Concrete pavement thickness design results

The highway concrete pavement design was established according to the AASHTO 1993 design guide, based on the 28-day strengths of the concrete specimens with substituted BFS at ratios of 0, 15, 20, 25, and 30 wt. %. In the concrete road pavement thickness calculations, seven different project traffic situations and very weak soil (plastic clay) conditions were considered. In the project traffic selection, 1×10^6 standard axle load repetition was taken as low vehicle traffic, where the annual average daily heavy vehicle traffic (AADHVT) is less than 500, or in other words, $W_{8.2}$ is less than 3.1×10^6. Regarding heavy vehicle traffic, standard axle load repetitions of 5×10^6, 10×10^6, 50×10^6, 100×10^6, 200×10^6, and 400×10^6 were considered, where the AADHVT value is greater than 500. The common parameters used in the calculations are given in Table 12.
In addition, the minimum strength requirements adopted in the design of the concrete pavement are listed in Table 13 [27].
The S'_c and E_c values to be used in the concrete pavement design of the specimens produced for soils with very weak bearing strength (plastic clay) are given in Table 14.
In soils with very weak bearing strength (k = 150 pci), the pavement thicknesses (1×10^6, 5×10^6, 10×10^6, 50×10^6, 100×10^6, 200×10^6, and 400×10^6) for different project traffics were determined via Eq. (2). A graph showing the variation in pavement thickness with traffic is displayed in Figure 16.
Figure 16 shows that the concrete pavement thickness (D) of the BFS-added specimens decreased compared with the control

Table 12. Common parameters used in concrete pavement design

Parameter	Selected value
8.2 t equivalent single-axle load repetitions, $W_{8,2}$	1 × 10^6, 5 × 10^6, 10 × 10^6, 50 × 10^6, 100 × 10^6, 200 × 10^6 i 400 × 10^6
Load transfer coefficient, J	2.70
Drainage coefficient, C_d	1
Standard error of traffic forecast and performance forecast, S_0	0,35
For 95 % R_E standard normal deviation, ZR	-1.645
Loss of serviceability, ΔPSI (psi), ΔPSI = P_0 - P_t	2

Table 13. Minimum characteristic compressive, flexural, and splitting-tensile strength values in the design of road pavement concrete

Characteristic cube compressive strength, f_{ck} [N/mm^2]	**Flexural strength, f_{cbt}** [N/mm^2]	**Splitting tensile strength, f_{sk}** [N/mm^2]
Min. C 30/37	Min. 4.50	Min. 3.30

Table 14. S'_c and E_c values of concrete specimens

Mixture code	**Characteristic cube compressive strength (28 day)** [MPa]	**Splitting tensile strength (28 day)** [MPa]	**S'_c - Flexural strength (28 day)** [MPa]	**E_c, (Ec = 6750 · S'_c)** [MPa]
(K-C)	49.24	5.02	5.97	40.297.50
(C15B)	54.15	5.28	6.17	41.647.50
(C20B)	56.28	5.43	6.35	42.862.50
(C25B)	52.14	5.38	6.30	42.525.00
(C30B)	51.30	5.34	6.24	42.120.00

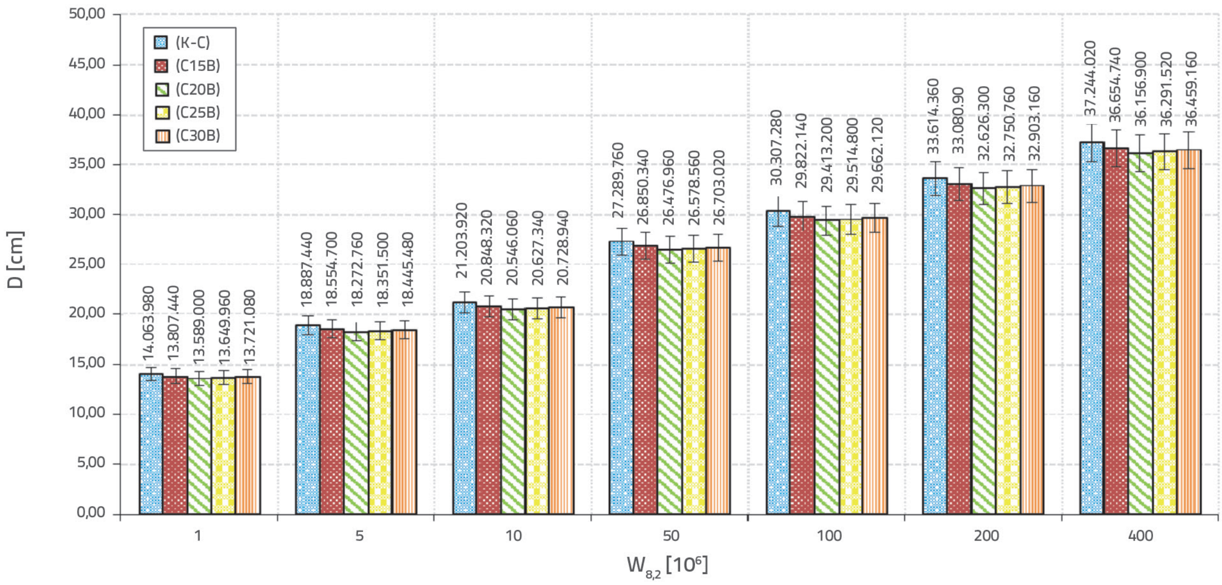

Figure 16. $W_{8,2}$ – D change for specimens considering soils with very weak bearing strength

specimen in soils with weak bearing strength. This decrease was calculated as follows for 1×10⁶, 5×10⁶, 10×10⁶, 50×10⁶, 100×10⁶, 200×10⁶, and 400×10⁶ project traffics, respectively:
- 1.82 %, 1.76 %, 1.68 %, 1.61 %, 1.60 %, 1.59 %, and 1.58 % in (C15B) specimen,
- 3.38 %, 3.25 %, 3.10 %, 2.98 %, 2.95 %, 2.94 %, and 2.92 % in (C20B) specimen,
- 2.94 %, 2.84 %, 2.72 %, 2.61 %, 2.61 %, 2.57 %, and 2.56 % in (C25B) specimen,
- 2.44 %, 2.34 %, 2.24 %, 2.15 %, 2.13 %, 2.12 %, and 2.11 % in (C30B) specimen.

4.2.2. Cost analysis results

Prices in Tekirdağ province in April, 2022, were considered for the cost analysis of the road concrete pavement thickness of the control and BFS-added specimens. The 20-cm-thick plentmix foundation (PMT) recommended by AASHTO under the concrete slab was not included in the cost analysis as it was applied for all specimens. The unit prices used within the scope of cost analysis are presented in Table 15; those for the control and BFS-added specimens were calculated using this information, and the results are provided in Table 16.

Table 15. Unit prices for cost analysis

Materials	Unit	Unit price [$]
Cement (3,80 g/cm³)	$/Ton	102.50
Mineral additive (2,90 g/cm³)		38.89
Water		1.15
Aggregate 0 – 5 mm (2,77 g/cm³)		32.45
Aggregate 5 – 11 mm (2,79 g/cm³)		28.50
Aggregate 11 – 22 mm (2,80 g/cm³)		30.40
Chemical additive (1,08 g/cm³) (a new generation of superplasticizer)		1100

Table 16. Unit prices of control and BFS-added specimens

Mixture code	Binder [kg/m³]		Aggregate [kg/m³]			Water [kg/m³]	Super plasticizer [kg/m³]	Total cost [$]	The cost of 1 m² and 1 cm thick [$]
	Cement	BFS	0 – 5 [mm]	5 – 11 [mm]	11 – 22 [mm]				
(K-C)	450,00	0.00	410	709	746	180	6	109.12	1.09
(C15B)	382,50	67.50	409	707	744			104.68	1.05
(C20B)	360,00	90.00	409	707	744			103.25	1.03
(C25B)	337,50	112.50	409	706	743			101.76	1.02
(C30B)	315,00	135.00	409	706	743			100.32	1.00

Within the scope of the study, the cost analysis of the specimens is presented in Figure 17. As can be seen, there is a cost reduction of at least 5.59 % and at most 10.30 % regarding the thickness of the pavement layer for different project traffics (1×10^6, 5×10^6, 10×10^6, 50×10^6, 100×10^6, $200\times1\,0^6$ and 400×10^6) in the cases of 15, 20, 25, and 30 wt. % BFS-reinforced concrete compared with the control specimens in the concrete pavement thickness design.

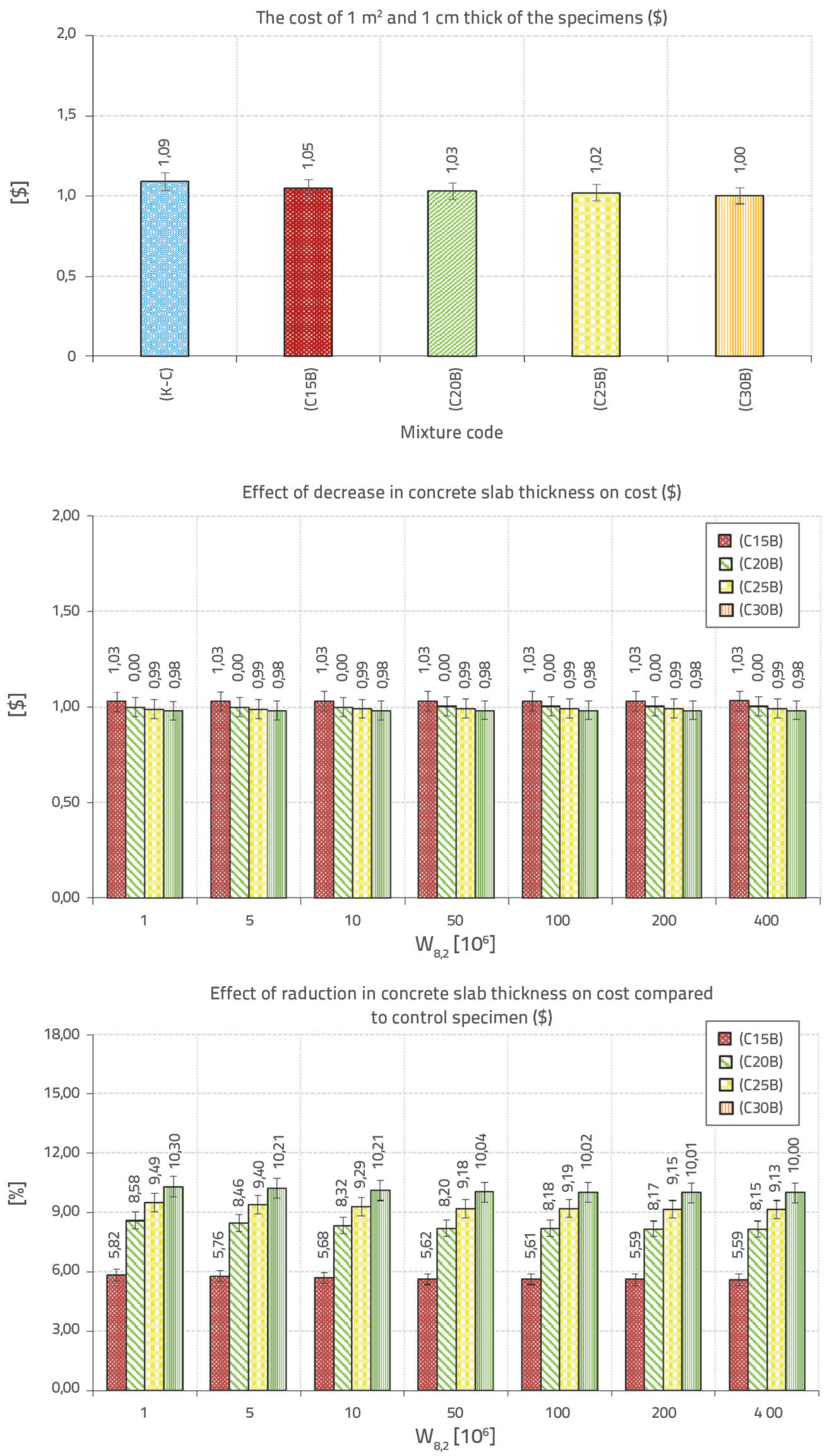

Figure 17. Cost analysis results of control and BFS-added specimens

5. Conclusions

In this study, the mechanical properties of concrete pavements prepared by substituting BFS in different proportions for cement as a binder were investigated, and the effects of BFS on concrete pavement thickness and cost were examined considering building on soil with weak bearing strength. The results obtained from the research are summarized below.

- By substituting BFS for cement at ratios of 0, 15, 20, 25, and 30 wt. %, a more workable and flowable concrete characteristic was obtained compared with the control mixture.
- With BFS substitution, the compressive strength of the specimens subjected to 7 days of curing time decreased, while those of the 28- and 90-day specimens increased. The highest increases occurred at 20wt. %BFS (C20B) compared with the control specimen, of 14.30 % and 15.90 % for the 28- and 90-day specimens, respectively At this ratio, the increase in compressive strength continued with prolonged curing time.
- According to the flexural strength results, the flexural strength of all 7-, 28-, and 90-day specimens increased with the BFS additive compared with the control specimens. The highest increases occurred for 20wt. %BFS (C20B), of 6.42 % and 9.03 % for the 28- and 90-day specimens, respectively. Thus, the curing time significantly affects the flexural strength of the specimens containing additive.
- According to the results of splitting-tensile strength, an increase in strength up to 20wt.%BFS (C20B) compared with the control specimens occurred in 7-day concrete specimens, followed by a decrease. However, although there was an increase in the specimens cured for 28 and 90 days,

the highest strength values were obtained for 20wt. %BFS (C20B), of 8.17 % and 6.26 %, respectively. According to these results, with advancing curing time, the splitting-tensile strengths of the specimens containing additive decreased at 28 days of curing.
- As a result of the freeze-thaw test, the highest strength loss (increase in weight) occurred in the concrete specimens containing 15 % BFS compared with the control specimen. A significant decrease in mass loss was found in the 20, 25, and 30 wt. % BFS-substituted concrete specimens compared with the control specimens. In this context, it is considered that the freeze-thaw resistance of concretes increases with an increase in the amount of BFS, starting from 15 wt. % BFS, and this increase is because BFS reduces the internal stresses in the concrete exposed to freezing.
- As a result of the calculations, it was determined that the concrete pavement thickness of the BFS-reinforced specimens to be built on soils with very weak bearing strength (i.e., plastic clay) under different project traffic loads could be decreased by 1.58 % to 3.38 % and the costs by 5.59 % to 10.30 %.
- In the present study, considering the 20wt. %BFS (C20B) ratio, at which BFS-added concrete strengths peak, both the cost of cement to be used and the carbon emission created by the cement will decrease. Moreover, the physical damage caused by BFS to the environment will be eliminated and an added value will be provided to the economy.

As a result of the study, the compressive, flexural, and splitting-tensile strength conditions required for concrete pavement design were met, and the rigid road pavement layer thicknesses and construction costs were reduced with the use of BFS instead of cement on soils with very weak bearing strength under different traffic loads.

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REFERENCES

[1] Gáspár, L., Bencze, Z.: Increasing the life expectancy of road pavements, GRAĐEVINAR, 72 (2020) 6, pp. 515-522, https://doi.org/10.14256/JCE.2644.2019

[2] Shafigh, P., Hashemi, M., Nam, B.H., Asadi, I.: Laboratory comparison of roller-compacted concrete and ordinary vibrated concrete for pavement structures, GRAĐEVINAR, 72 (2020) 2, pp. 127-137, https://doi.org/10.14256/JCE.2572.2018

[3] Pradena, M., Houben, L.: Influence of early-age concrete behaviour on concrete pavements performance, GRAĐEVINAR, 69 (2017) 9, pp. 875-883, https://doi.org/10.14256/JCE.1931.2016

[4] Lin, S.K., Wu, C.H.: Improvement of bond strength and durability of recycled aggregate concrete incorporating high volume blast furnace slag, Materials, 14 (2021) 13, pp. 3708, https://doi.org/10.3390/ma14133708

[5] Boran, H., Günaydın, O., Güçlüer, K.: Investigation of engineering properties of blast furnace slag additive mortars, MANAS Journal of Engineering, 8 (2020) 2, pp. 138-143, https://doi.org/10.51354/mjen.795891

[6] Kavitha, S.M., Venkatesan, G., Avudaiappan, S., Flores, E.S.: Mechanical and flexural performance of self-compacting concrete with natural fiber, Revista De La Construcción, 19 (2020) 2, pp. 370-380, https://doi.org/10.7764/rdlc.19.2.370

[7] Highways Concrete Road Pavement Project Guidelines, (2019), Türkiye.

[8] Pradena, M., Houben, L., Cesar, A.: Experimental evaluation of load transfer efficiency of non-dowelled concrete pavements, GRAĐEVINAR, 74 (2022) 3, pp. 179-187, https://doi.org/10.14256/JCE.2844.2019

[9] Wu, F., Li, H., Yang, K.: Effects of mechanical activation on physical and chemical characteristics of coal-gasification slag, Coatings, 11 (2021), pp. 902 https://doi.org/10.3390/coatings11080902

[10] Fernandez, L., Malhotra, V.M.: Mechanical properties, abrasion resistance and chloride permeability of concrete incorporating granulated Blast-Furnace Slag (BFS), Cement, Concrete and Aggregates, 12 (1990) 2, pp. 87-100, https://doi.org/10.1520/CCA10276J

[11] Öner, A., Akyüz, S.: An experimental study on optimum usage of GGBS for the compressive strength of concrete, Cement and Concrete Composites, 29 (2007) 6, pp. 505-514. https://doi.org/10.1016/j.cemconcomp.2007.01.001

[12] Al-Baijat, H., Sarireh, M.: The use of fine blast furnace slag in ımprovement of properties of concrete, Open Journal of Civil Engineering, 9 (2019) 2, pp. 95-105, https://doi.org/10.4236/ojce.2019.92007

[13] Menéndez, G., Bonavetti, V., FIrassar, E.: Strength development of ternary blended cement with limestone filler and blast furnace slag, Cement and Concrete Composites, 25 (2003) 1, pp. 61-67, https://doi.org/10.1016/S0958-9465(01)00056-7

[14] Rodrigues, A.L.M.V., Mendes, Á.Á.F., Gomes, V., Battagin, A.F., Saade, M.R.M., Da Silva, M.G.: Environmental and mechanical evaluation of blended cements with high mineral admixture content. Structural Materials, 9 (2022), pp. 1-11, https://doi.org/10.3389/fmats.2022.880986

[15] Yeau, K.Y., Kım, E.K.: An experimental study on corrosion resistance of concrete with ground granulated blast furnace slag, Cement and Concrete Research, 35 (2005) 7, pp. 1391-1399, https://doi.org/10.1016/j.cemconres.2004.11.010

[16] Lee, H.S., Wang, X.Y., Zhang, L.N., Koh, K.T.: Analysis of the optimum usage of slag for the compressive strength of concrete. Materials, 8 (2015) 3, pp. 1213-1229, https://doi.org/10.3390/ma8031213

[17] Shariq, M., Prasad, J., Masood, A.: Effect of GGBFS on time dependent compressive strength of concrete. Construction and Building Materials, 24 (2010) 8, pp. 1469-1478, https://doi.org/10.1016/j.conbuildmat.2010.01.007

[18] Jin-Young, L., Jin-Seok, C., Tian-Feng, Y., Young-Soo, Y., Denis, M.: Comparing properties of concrete containing electric arc furnace slag and granulated blast furnace slag, Materials, 12 (2019) 9, pp. 1-11, https://doi.org/10.3390/ma12091371

[19] TS EN 197-1.: Cement-Part 1: General cements-composition, properties and conformity criteria, Turkish Standards Institute, 2012.

[20] TS EN 933-1.: Experiments for geometric properties of aggregates Part 1: Determination of particle size distribution-sieving method. Turkish Standards Institute, 2012.

[21] TS EN 1097-6.: Experiments for mechanical and physical properties of aggregates - Part 6: Determination of particle density and water absorption rate. Turkish Standards Institute, 2002.

[22] TS EN 1097-2.: Experiments for mechanical and physical properties of aggregates Part 2: Methods for determination of fragmentation resistance. Turkish Standards Institute, 2000.

[23] TS EN 1367-4.: Tests for thermal properties of aggregates - Part 4: Determination of drying shrinkage, Turkish Standards Institute, 2009.

[24] CAN/CSA-A23.2-25A-14.: Test Method for Detection of Alkali-Silica Reactive Aggregate by Accelerated Expansion of Mortar Bars, Canadian Standards Association, 2014.

[25] TS 781 ISO 758.: Density determination at -20°C for liquid chemical products used in industry, 1998.

[26] TS EN 12350-2.: Concrete - Fresh concrete tests - Part 2: Slump test, 2019.

[27] TCK Concrete Road Pavements Technical Specification.: Turkey, 2019.

[28] AASHTO Guide for Design of Pavement Structures: American Association of State Highway and Transportation Officials, Washington, D.C., 1993.

[29] Humad, A.M., Kothari, A., Provis, J.L., Cwirzen, A.: The effect of blast furnace slag ratio on setting, strength, and shrinkage of alkali-activated pastes and concretes. Materials, 6 (2019) 9, pp. 1-10, https://doi.org/10.3389/fmats.2019.00009

[30] Aghaeipour, A., Madhkhan, M.: Effect of ground granulated blast furnace slag (GGBFS) on RCCP durability, Construction and Building Materials, 141 (2017), pp. 533–541, https://doi.org/10.1016/j.conbuildmat.2017.03.019

[31] Huynuh, T.P., Ho, L.S., Ho, Q.V.: Experimental investigation on the performance of concrete incorporating fine dune sand and ground granulated blast-furnace slag, Construction and Building Materials, 347 (2022), pp. 128512, https://doi.org/10.1016/j.conbuildmat.2022.128512

[32] Elsayed, M., Tayeh, B.A., Aisheh, I.A., El-Nasser, N.A., Elmaaty, M.A.: Shear strength of eco-friendly self-compacting concrete beams containing ground granulated blast furnace slag and fly ash as cement replacement, Case Studies in Construction Materials, 17 (2022), pp. e01354, https://doi.org/10.1016/j.cscm.2022.e01354

[33] Dabhekar, K.R., Nagarnaik, P.B, Pawade, P.Y.: Relationship between compressive strength and UPV for concrete with partial replacement of GGBFS, International Journal of Civil Engineering and Technology, 8 (2017) 5, pp. 582-592, http://iaeme.com/Home/issue/IJCIET?Volume=8&Issue=5

[34] Yang, J.M., Yoo, D.Y., Kim, Y.C., Yoon, Y.S.: Mechanical properties of steam cured high-strength steel fiber-reinforced concrete with high-volume Blast Furnace Slag, International Journal of Concrete Structures and Materials, 11 (2017), pp. 391-401, https://doi.org/10.1007/s40069-017-0200-0

[35] Ahmad, J., Martínez-García, R., Szelag, M., Prado-Gil, J., Marzouki, R., Alqurashi, M., Hussein, E. E.: Effects of steel fibers (SF) and ground granulated blast furnace slag (GGBS) on recycled aggregate concrete, Materials,14 (2021) 24, pp. 7497, https://doi.org/10.3390/ma14247497

[36] Reiterman, P., Holčapek, O., Zobal, O., Keppert, M.: Freeze-thaw resistance of cement screed with various supplementary cementitious materials, Reviews on Advanced Materials Science, 58 (2019), pp. 66-74, https://doi.org/10.1515/rams-2019-0006