ŞIRNAK ÜNİVERSİTESİ FEN BİLİMLERİ DERGİSİ
SIRNAK UNIVERSITY JOURNAL OF SCIENCES

ISSN: 2667-7083
e-ISSN:2687-3796

Research Article

Use of Powdered Steel Slag in Cement-Bentonite Slurry Wall Construction

Davood TALEFIROUZ [1*], Erdal ÇOKÇA [2]

[1] MSc, Civil Engineering Department, Middle East Technical University, Ankara,Turkey; talefirouz@gmail.com
[2] Prof, Civil Engineering Department, Middle East Technical University, Ankara,Turkey; ecokca@metu.edu.tr
[*] Corresponding Author; talefirouz@gmail.com

Recieved / Gönderme tarihi: 04/11/2019
Accepted / Kabul tarihi: 21/04/2022

ABSTRACT

This paper presents a comprehensive laboratory investigation into the workability, permeability and unconfined compressive strength of powdered-steel-slag, lime-amended cement-bentonite backfills using several series of mixtures. Prepared mixtures comprise various proportions of cement, bentonite, powdered steel slag, and lime, tested for particle size distribution (PSD), liquid limit, plastic limit, permeability, and unconfined compressive strength (UCS). For each mixture, the effect of different curing times was investigated. The results show that the permeability of the powdered steel-slag, lime-amended cement-bentonite backfill is near enough to the 10^{-9} m/s (10^{-7} cm/s) required by standards. The laboratory observations clearly show that cement-bentonite-steel slag (CBS) backfill strengthens with time. When placed, the backfill is viscous liquid; later, it is a material strong enough to stand vertically. Amended mixtures, including 9% of bentonite content, give higher strength values and present lower permeability consider to other mixtures in slurry wall construction. In addition, the stiffness characteristics of the samples were investigated by determining the secant modulus of elasticity at 50%. Therefore, it is concluded that CB–powdered steel slag–lime blended mixtures are superior materials for constructing slurry walls.

Keywords: Cement-Bentonite; Permeability; Powdered Steel Slag; Secant Modulus; Slurry Wall; Unconfined Compressive Strength

Çimento-Bentonit Bulamaç Duvar İnşaatında Toz Çelik Cüruf Kullanımı

ÖZET

Bu makalede, çimento-bentonit-toz çelik cürufu-kireç karışımlarının, bulamaç hendeği duvarlarda dolgu maddesi olarak kullanılabilmesi için, işlenebilirlik, geçirgenlik ve serbest basınç dayanımı özelliklerinin araştırıldığı kapsamlı bir laboratuvar çalışması sunulmaktadır. Çeşitli oranlarda hazırlanan çimento-bentonit-toz çelik cürufu-kireç karışımlarının, tane boyu dağılımı (PSD), likit limit, plastik limit, geçirgenlik ve serbest basınç dayanımınlarına (UCS) bakılmıştır. Her karışım için, kür süresinin etkisi incelenmiştir. Sonuçlar, çimento-bentonit-toz çelik cürufu-kireç dolgu maddesinin geçirgenliğinin standartların gerektirdiği 10^{-9} m/saniye (10^{-7} cm/saniye) yakın olduğunu göstermektedir. Laboratuvar gözlemleri, bu çalışmada değerlendirilen çimento-bentonit-toz çelik cürufu-kireç (CBS) dolgu maddesinin mukavemetinin zamanla arttığını göstermektedir. Dolgu maddesi hendeğe yerleştirildiginde viskoz bir sıvı kıvamındadır; daha sonra, düşey olarak durabilecek kadar güçlü bir malzemeye dönüşmektedir. %9 bentonit içeren karışımlar, sadece daha yüksek mukavemet değerleri vermekle kalmayıp, aynı zamanda bulamaç duvarı için önemli olan, bu çalışmada test edilen diğer karışımlara göre daha düşük geçirgenlik değeri vermişlerdir. Ayrıca, numunelerin rijitlik özellikleri, sekant elastisite modülülün %50'sinde belirlenerek araştırılmıştır. Çimento-%9 bentonit-toz çelik cürufu- kireç karışımlarının bulamaç duvarı oluşturmak için uygun karışımlar olduğu sonucuna varılmıştır.

Anahtar Kelimeler: Çimento-Bentonit; Geçirgenlik; Toz Çelik Cürufu; Sekant Modülü; Bulamaç Duvar; Serbest Basınç Mukavemeti.

1. INTRODUCTION

Unlike soil-bentonite, cement-bentonite slurry walls harden in place and need no other backfill. This means self-hardened properties of CB are referred to as one-step construction and meanwhile as a final barrier wall. In this method, cement and typically other additives such as attapulgite or slag are used to improve slurry walls stability and overcome adjacent weaker ground soils. Hardening progression of CB takes several months and long-term investigations have revealed gradual permeability reduction with time (https://www.geo-solutions.com, 2017). The steel slag recycling rate in the world, on average, is over 80%. In addition, Steel Slag (BOF and EAF Slag) amount in Europe in 2012 was 24.7 Mt; however, about 13% of steel slag was not used and stored (TSPA, 2015).

In Turkey in 2014, 5.4 million tons of steel slag was produced as a by-product throughout steel making industry, 37% of it was recycled (as a cement additive, parquet, curb, rain gutter, ready-mixed concrete products, micronized granular products, asphalt aggregate, and as various sizes of filler material, etc.) and 63% was stored (TSPA, 2015). Therefore, alternative use possibilities should be investigated. In US, steel slag usage in cement production is common (PCA, 2005). There are also studies on the use of steel production slag as top cover in waste landfills, and it has been determined that fine steel slags can be used in impermeable top cover layer (Andreas et al., 2005). Khajeh et al. (2020) revealed that when basic oxygen furnace slag (BOFS) known as Steel Slag used for soil stabilization, gave the same environmental classification compared those provided by cement-lime-stabilized soils.

The above studies have strengthened the possibility that the powdered steel slag can be used in slurry wall construction as an additive and may give positive results. Therefore, the use of powdered steel slag in the slurry walls will eliminate both the storage costs and the need for natural mineral material. The slurry wall is a sealing method used in hydraulic earthworks to create an impermeable barrier to water. This sealing technique is often used in dykes, retention dams, and levees for leakage control. Cement-bentonite (CB) slurry walls using backfill comprising cement and Na-bentonite are used in construction projects to achieve low permeability. Amendments to this backfill, powdered steel slag and lime, may further decrease permeability. However, studies on the workability (the slump), permeability and strength of such powdered steel slag–amended cement-bentonite backfills for slurry walls are limited. The construction procedure involves trench excavation into the subsurface to the desired depth. Generally, $k \leq 10^{-7}$ cm/s is required for slurry walls used in containment applications (LaGrega et al., 2001).

Since CB slurry walls are being used as low-permeability barriers to groundwater flow, the value of permeability k of CB backfill materials plays an important role in constructing the wall (D'Appolonia, 1980; Millet & Perezz, 1981; Spooner et al., 1984; Ryan, 1987; Evans & Dawson, 1999; Bodocsi et al., 1995; Filz, 1996). In the last two decades, slag-CB slurry walls have been used extensively in the U.K. Due to the intrinsic variability of material mixes, the U.K. National Specification (ICE, 1999) requires a laboratory permeability value of no more than 10^{-7} cm/s for a 90-days-cured specimen. For slag-CB slurry walls, permeability changes with curing times. Opdyke & Evans (2005) and Jefferis (2008) reported on the change in permeability during the early stages of curing. The horizontal deflection of the cured vertical CB slurry wall relies on the permeability and strength parameters of the wall (Ruffing et al., 2010). Manassero et al. (1995) stated that fly ashes, furnace slags, minerals and other by-products could be used for cement bentonite mixtures, and when these materials are used in backfill sealing mixtures, unit weight and chemical resistance increases, void ratio, permeability, diffusion coefficient and unit cost decreases.

The behavior of slurry walls for short-term and long-term has been studied by researchers (Carreto et al., 2015). Du et al. (2015) proved that sodium bentonite and calcium bentonite reduce permeability if used in barrier walls. Xu et al. (2016) reported that permeability results could be improved with appropriate bentonite content. According to Sreedharan & Puvvadi (2013), in the long-term, pozzolanic cementitious material reaction and cement hydration not only improve slurry wall strength but also cause to gradual reduction in permeability. Carreto (2014) investigated that the pozzolanic reaction during cement hydration occurring in the hardened specimens enable the slurry to endure considerable plastic deformation before cracking at substantial shear stress levels. This paper describes an experimental study on powdered steel slag and lime as stabilizers for cement-bentonite (CB) slurry used in building vertical barrier walls. The key element is developing a mixture of materials that can reduce the permeability and improve the strength of CB slurry walls. Time-dependent behavior of the backfill and, in particular, the change in shear strength and permeability with aging were also investigated. Modulus of elasticity $E_{50(u)}$ at 50% of ultimate stress-strain rate was obtained based on unconfined compression strength test results.

2. MATERIALS AND METHODS

2.1 Materials

In this study, cement type I, powdered steel slag, lime, and sodium bentonite were used as the main materials. Karakaya sodium bentonite produced in Turkey was used for bentonite-water slurry preparation. The mineralogical and index/composition properties of Karakaya bentonite are given in Tables 1 and 2, respectively. Cement production, however, leads to carbon dioxide (CO_2) emission up to 8% annually in the world. Aiming to reduce cement utilization in construction projects, more studies need to be done to use cementitious waste materials as a partial replacement of cement. Steel slag is produced as a by-product of steel production.

Table 1. Mineralogical properties of the Karakaya bentonite.

Mineralogical Component	By weight (%)
Quartz	5
Smectite	71
Zeolite	19.50
Others	4.50

Table 2. Index and compaction properties of the Karakaya bentonite.

Parameter	Quantity
Dry density(Mg/m^3)	0.8
Natural density(Mg/m^3)	0.87
Water content (%)	8
Specific gravity	2.17
Void ratio (%)	1.89
Porosity (%)	65
Liquid limit (%)	320
Plastic limit (%)	50
Plasticity Index (%)	270

Parameter	**Quantity**
Cation exchange capacity (meq/100 g)	55-60

Steel slag naturally contains magnesium and free lime. These two ingredients never react with silicate in other materials and can expand and hydrate after mixing with water or even in humid environments. The partial replacement of cement with slag is now widely accepted in geotechnical practices (Joshi et al., 2010). Steel Slag's tendency to expand is beneficial in some geotechnical applications. This expansion, for instance, can prevent undesired cracks that would increase permeability. Therefore, this characteristic of steel slag, when mixed with enough water to create a 20% powdered steel-slag slurry, could be helpful for slurry wall construction. The steel slag for this study was produced in the Erdemir Iron and Steel Plant in Turkey. The steel slag had been gravel-sized before it was grinded by mechanical grinding into fine particles in the laboratory (Figure 1). The chemical composition of the steel slag is given for comparison in Table 3. Compared to cement, the hydration rate of steel slag at the early ages is much slower (Shi, 2004). However, this rate intensifies at either 90 days of curing time or later, even more than cement (Wang et al., 2018). Slag basicity can be extracted from ($R=\frac{CaO}{(SiO2+P2O5)}$). Mason (1944) represented that steel slag cementitious activity based on its basicity can be divided into three categories: smaller than 1.8 for lower alkalinity, 1.8-2.5 for medium alkalinity and larger than 2.5 for high alkalinity.


(a) (b)

Figure 1. Utilized steel slag, gravel size (a), powdered steel slag (b).

In this study, the chemical composition of steel slag indicates that the R-value is 2.89, which represents high alkalinity steel slag. Relationship between chemical composition and basicity of steel slag whereas alkalinity is greater than 2.5 represents main minerals as tricalcium silicate slag. The greater the steel slag's basicity value is, the more cementitious properties it owns (Dhoble & Ahmed, 2018). Besides, lime saturation factor (LSF) must be evaluated on cementitious material (based on chemical properties) where hydration rate and further strength achievement at early ages are assigned. Unless steel slag has (LSF) value of greater than one, the addition of lime content is needed to improve the early strength of the mixtures. Where LSF=$\frac{CaO}{(2.8SiO_2+1.2Al_2O_3+0.6Fe_2O_3)}$, the steel slag's (LSF) value in this study is 0.8. Therefore, adding a few proportions of lime content to the mixtures not only can improve the initial hydration rate but also it may accelerate early strength gain.

2.2 Methods

Index properties, slump, permeability, and unconfined compressive strength values of the mixtures were evaluated to contemplate whether they meet the minimum requirements. The permeability and unconfined compressive strength of cement–bentonite–powdered steel-slag–lime mixtures for various curing times were investigated. Wang et al., (2013) indicated that powdered-steel slag produces more hydration rate than coarse aggregate steel slag at the early age of curing time. The consistency required the backfill-slurry mixture to displace the trench slurry correlates to a slump ranging from 100 mm to 150 mm (4 to 6 in.) (Opdyke & Evans, 2005). Prepared fresh mixtures also have a slump of 100 mm to 150 mm. In this study, the slurry was 20% cementitious material content by dry mass and 80% bentonite-water slurry (Figure 2). Opdyke & Evans, (2005) gave the Slag-CB slurry preparation with 20% of cementitious material (75-80% of slag-20-25% of cement) mixed in 80% of bentonite water slurry (5% Bentonite+ 95% Water). The percentages of supplementary cementitious materials replaced by Portland cement for this experiment were 0%, 20%, 50%, and 80%. All samples were cured in a room at 100% humidity. Samples were tested at 7 days, 28 days, and 90 days of curing time. Cured specimens were subjected to permeability and unconfined compression tests.

Table 3. Chemical composition ranges of steel slag.

Constituent	Steel Slag Composition (%)
Aluminium Oxide (Al_2O_3)	1.76
Calcium Carbonate ($CaCO_3$)	67
Calcium Oxide (CaO)	47
Iron (III) Oxide (Fe_2O_3)	20
Magnesium Oxide (MgO)	7.20
Manganese Oxide (MnO)	6.50

Constituent	Steel Slag Composition (%)
Silicon Dioxide (SiO_2)	15.57
Sulphur (S)	<0.1
P_2O_5	0.68

2.2.1 Sample Preparation

In this experimental study, four types of material (i.e., sodium bentonite, cement, steel slag, and lime) in different mixture designs were examined. Index tests (Atterberg limit, specific gravity, and particle size distribution) were carried out for all samples. Specimens were prepared for permeability and unconfined compressive strength tests. Mixture designs have three series (Figure 2). For the first series, cement was replaced by powdered steel slag at 0%, 20%, 50%, and 80%, respectively. In the second series, the mixture included cement replacement of 50% (B5-C50-S50) was amended with 5% lime. Aiming to increase the strength of a mixture, a lime content of 5% in one instance was replaced by 5% portion of powdered steel slag, and in another instance replaced by a 5% portion of cement (i.e., B5-C50-S45-L5 and B5-C45-S50-L5, Mixtures). In the third series, in order to reduce permeability, bentonite content in batch slurry preparation for the same mixture design of the second series has increased from 5% to 9% (i.e., B9-C50-S45-L5 and B9-C45-S50-L5, Mixtures). Since the reaction rate of slag is inappreciable, an alkaline activator such as lime would have some ability to speed up the reaction rate (Talefirouz et al., 2016). A bentonite content of 9% in the batch slurry was used to improve the mixtures, including 5% lime content in the third series. For all series, specimens cured for 7 days, 28 days, and 90 days were subjected to permeability and strength tests.

2.2.2 Preparation of Batch Slurry

The batch slurry portion in the samples was 80% of the total mixture weight, while the remaining 20% of the mixtures was cementitious material. Two mixtures of batch slurry were prepared with different bentonite contents. First, a mixture was prepared using 5% bentonite by dry weight mixed with 95% distilled water. For the second, 9% bentonite by dry weight was mixed with 91% distilled water. Distilled water at 22˚C has a pH value of 6.69. Bentonite-water slurry at 19.5˚C with 5% and 9% bentonite content has pH values of 9.1 and 8.87, respectively.

2.2.3 Preparation of Test Specimens

Cementitious material and bentonite were put into the oven to dry a day before sample preparation. During the mixing days, cementitious materials were mixed according to the mix design. Dry materials were mixed by hand using a steel spatula for five minutes in a plastic pan then passed through a number 40 sieve (particle size 0.420 mm) at least for five times to obtain a uniform mixture. The total mixture was 20% cementitious material by weight. For instance, 5 kg of prepared slurry comprised 1 kg of cementitious material and 4 kg of batch slurry. Plastic cylindrical molds of 5 cm in internal diameter, 6.3 cm in external diameter, and 10 cm in height were used. Prepared specimens were placed in the 100% humidity room at a temperature of 20 ±2 ˚C. A pair of undamaged specimens were used for the permeation and strength tests.

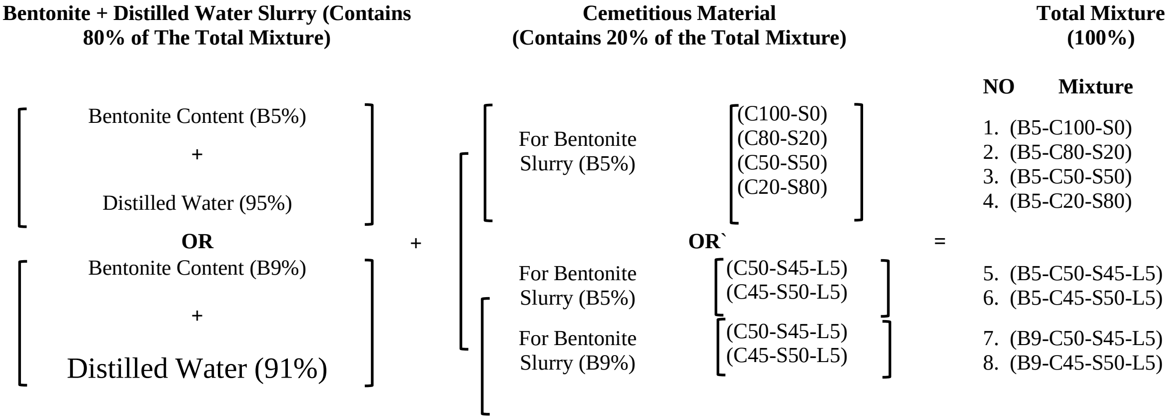


Figure 2. Mixture Design (B: Bentonite, C: Cement, S: Powdered Steel slag, L: Lime).

2.2.4 Test Procedure

2.2.4.1 Index Tests

In geotechnical practice, the conventional hydrometer test method is typically used to determine the particle size distribution (PSD) of fine particles. It takes 24 hours. However, cementitious material starts to flocculate within five minutes. Thus, the PSDs of mixtures in this experiment were determined by the laser diffraction method. A laser diffraction system with a wavelength of about 633 nm was used for PSD analysis in this study. It was adjusted to measure particle sizes between 0.001 and 2 mm. An electrical instrument having a capacity of 1 L was used for sample preparation. The specific gravity (Gs) of cementitious material cannot be determined using ASTM D854-10 because it covers the determination of the specific gravity of soil solids by pycnometer—the procedure takes more than 3 hours, so that flocculation can occure. Thus, Gs test was determined according to ASTM C188-09. For this method, kerosene was placed in a graduated flask to determine volume change. To determine the Gs of cement, the standard specifies that 64 g of cement be used, and for other mixtures including pozzolanic material, 50 g were used. Around 200 g of the dry mixture was set aside for Atterberg limit tests. The liquid limit and plastic limit of the mixtures were determined by wet preparation methods according to ASTM D4318-10. Since the initial setting time (hydration) of the cementitious material is not more than 15 minutes, the test procedure could not adhere to the standard’s requirement of a hydration time of at least 16 hours in a humid room. As soon as the shape of the Casagrande cup was attained by fresh mixtures, the Atterberg limit was tested within ten minutes of mixing.

2.2.4.2 Permeability and Strength Tests

The permeability tests were carried out according to ASTM D5084-03 Method E—Constant Volume-Constant Head, using a triaxial cell permeameter system. The value of the hydraulic gradient was 10 in the flexible-wall permeability test. Cured samples were taken from the humid room on test days, and specimens of similar size were used for permeability and strength tests. The specimens were tested for unconfined compressive strength according to ASTM D2166-06.

3. RESULTS AND DISCUSSION

Index properties of the mixtures are given in Table 4, which shows PSD, Gs, and Atterberg limit test results of the mixtures prepared as 20% cementitious material. The Gs values of cement, bentonite, steel slag, and lime are 2.89, 2.17, 3.40, and 2.27, respectively. In the proposed mixtures of B9-C50-S45-L5 and B9-C45-S50-L5, compared to the CB reference mixture (C-S with 5% B), the amounts of clay and silt-sized material are decreased, and the amount of sand-sized material is increased. In addition, Gs is increased, and Atterberg limit values are decreased.

3.1 Permeability (*k*)

Backpressure of 100 kPa and cell pressure of 200 kPa was kept constant during permeability measurement. Permeability values were founded under 100 kPa effective confining stress consistent with the same value provided by (Opdyke & Evans, 2005). Effluent and influent volumes were recorded. All specimens were subjected to permeability tests after 7 days, 28 days, and 90 days of curing time. Naturally, permeability tests for each sample took two or three days,but never more than four days. Permeability values of the mixtures are given in Table 5. Sample with cement replacement of 50% was also examined by adding 5% lime and 9% bentonite content to the batch slurry. Changing the mixture to 9% bentonite shows that permeability reduces between 28 days and 90 days of curing time. It reduced from 5.4×10^{-7} cm/s to 4.3×10^{-7} cm/s and from 4.3×10^{-7} cm/s to 3×10^{-7} cm/s, respectively. The permeability of samples containing batch slurry of 5% bentonite increased between 28 days and 90 days. It should be noted that the permeability test results in the laboratory are lower than those measured in the field (Oweis & Khera, 1990).

Table 4. Index properties of the mixtures.

NO	Mixture	Clay size (%)	Silt size (%)	Sand size (%)	Gs	LL (%)	PL (%)	I_p (%)
1	B5-C100-S0	24	76	0	2.82	39	25	14
2	B5-C80-S20	10	76	14	3.10	39	18	21
3	B5-C50-S50	13	76	11	3.00	37	22	15
4	B5-C20-S80	15	77	8	2.89	44	24	20
5	B5-C50-S45-L5	12	76	12	2.94	37	23	14
6	B5-C45-S50-L5	13	81	6	2.97	31	21	10
7	B9-C50-S45-L5	12	75	13	2.85	30	19	11
8	B9-C45-S50-L5	12	73	15	2.95	31	21	10

Note: *C=cement, S= powdered steel slag, L= Lime B*: Bentonite % in batch slurry*

In the proposed mixtures (B9-C50-S45-L5) and (B9-C45-S50-L5), compared to the CB reference mixture (C with 5% B), permeability decreased by 6.8 times in 28 days of curing and by 8.6–12 times in 90 days of curing. Low permeability criterion is the initial design consideration in slurry walls utilized for groundwater control application. A permeability of $1\times10^{\wedge-7}$ cm/s is generally required. However, a value of $1\times10^{\wedge-6}$ or higher may be sufficient for some groundwater control purposes (Opdyke & Evans, 2005).

3.2 Unconfined Compressive Strength (*qu*)

In this study, the freshly placed mixtures had low shear strengths. This is not surprising since the slurry is placed as a viscous liquid. The results shown in Table 5 reveal a detectable change in the shear strength of the backfill during one week, one month, and three months. The loading rate of the compression machine was adjusted to 0.5 mm/min. Since steel slag has a high creation temperature, C_3S is utterly advanced in steel slag those in cement along with highly compacted structure, which cause to reduce in hydration rate of steel slag (Wang et al., 2018). Powdered steel slag used in the mixtures affects hydration rate. The hydration rate of the samples has a particular effect on strength development. The higher the hydration rate is, the quicker the strength achievement is possible. Cementitious activity of steel slag shows that strength gaining of this material takes more than other pozzolanic materials like class C of fly ash and ground granulated blast furnace slag (GGBFS). Results presented in this paper clearly illustrate that gaining strength of samples, including powdered steel slag needs several months to satisfy the required results due to lower hydration rate at the initial months.

Providing appropriate curing situation for concrete and mortar samples, ordinary Portland cement gains at least 90% of its ultimate strength at the age of 28 days. While cement associated with steel slag shows lower strength progression at the first month, *qu* increases in proportion between 90 days and 28 days' age can be considered as the strength growth rate (SGR) for amended mixtures in which SGR=$\frac{qu\ (90)}{qu(28)} \times 100$. The SGR for all samples, including cement replacement of 50% or more, was 117% to 457% (Table 5). The idea behind of the strengthening of the mixture, including cement replacement of 50%, is that; the SGR of 330% at 90 days of aging was achieved. Since this mixture did not provide the minimum strength requirement of 100 kPa at 28 days of aging, it was decided to amend it with 5% of lime, and with the addition of bentonite by dry mass. It is apparent from this study that the highest value was achieved for cement replacement of 50% with 9% of bentonite content. In the proposed mixtures of B9-C50-S45-L5 and B9-C45-S50-L5, compared to the CB reference mixture (C with 5% B), Unconfined Compressive Strength increased significantly. It should be noted that the amount of cementitious component substances like C_2S and C_3S would definitely be lessened due to the partial replacement of cement by powdered steel slag, and the powdered steel slag slightly increases the strength of the specimens.

Table 5. Permeability and Strength test values.

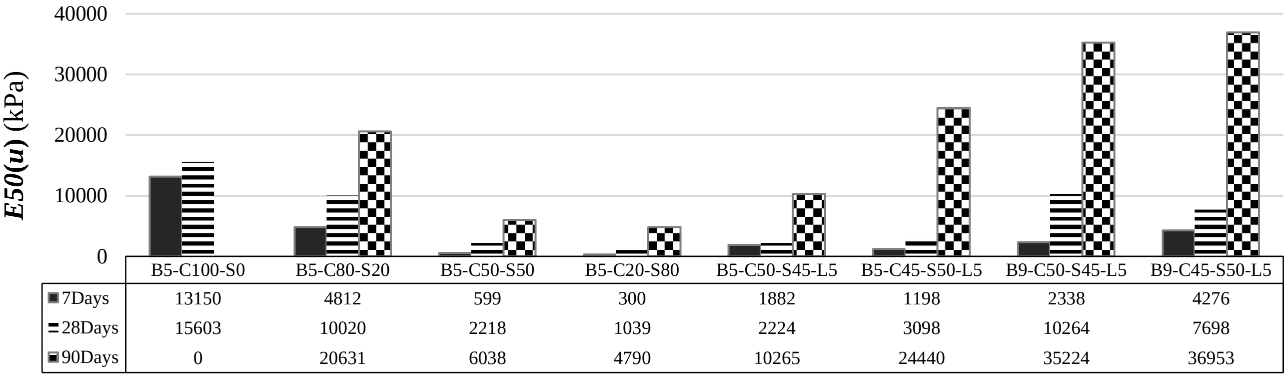
NO	**Mixture**	**Permeability** ***k*** **(cm/sec)**			**Unconfined Compressive Strength** q_u **(kPa)**			**Strength Growth Rate (SGR) (%)**
		Curing Time (day)						
		7	**28**	**90**	**7**	**28**	**90**	
1	B5-C100-S0	8.09×10^{-6}	3.65×10^{-6}	-	100	132	-	-
2	B5-C80-S20	1.14×10^{-6}	7.68×10^{-7}	4.90×10^{-6}	35	71	72	101
3	B5-C50-S50	1.00×10^{-6}	1.69×10^{-6}	1.80×10^{-6}	10	13	43	331
4	B5-C20-S80	7.00×10^{-7}	9.92×10^{-7}	8.70×10^{-7}	6	18	25	139
5	B5-C50-S45-L5	6.65×10^{-7}	2.98×10^{-7}	3.30×10^{-6}	11	20	42	210
6	B5-C45-S50-L5	7.90×10^{-7}	3.43×10^{-7}	1.60×10^{-6}	14	23	105	457
7	B9-C50-S45-L5	4.00×10^{-7}	5.39×10^{-7}	4.24×10^{-7}	29	105	123	117
8	B9-C45-S50-L5	4.62×10^{-7}	4.30×10^{-7}	3.00×10^{-7}	35	95	189	199

Note: C=cement, S= powdered steel slag, L= Lime, B*: Bentonite % in batch slurry

Shi (2004) provided comprehensive investigation on long-term strength development of cement-powdered steel slag mortar, which strength achievement for the same sample at 5000 days of curing age was two times greater than those obtained at 90 days' age. This is to say, existing a few amounts of lime content (5%) significantly affects the early strength gain of powdered steel slag where a lower hydration rate at initial months would be problematic. Such a phenomena is esteem from the pozzolanic reaction between powdered-steel slag and lime. Furthermore, incorporating further bentonite content in batch slurry until 9% by dry mass reduces w/c ratio and causes to increase in strength directly. It should be noted that in slurry wall construction, bentonite content of more than 9% in batch slurry preparation leads to delivering unworkable mixture.

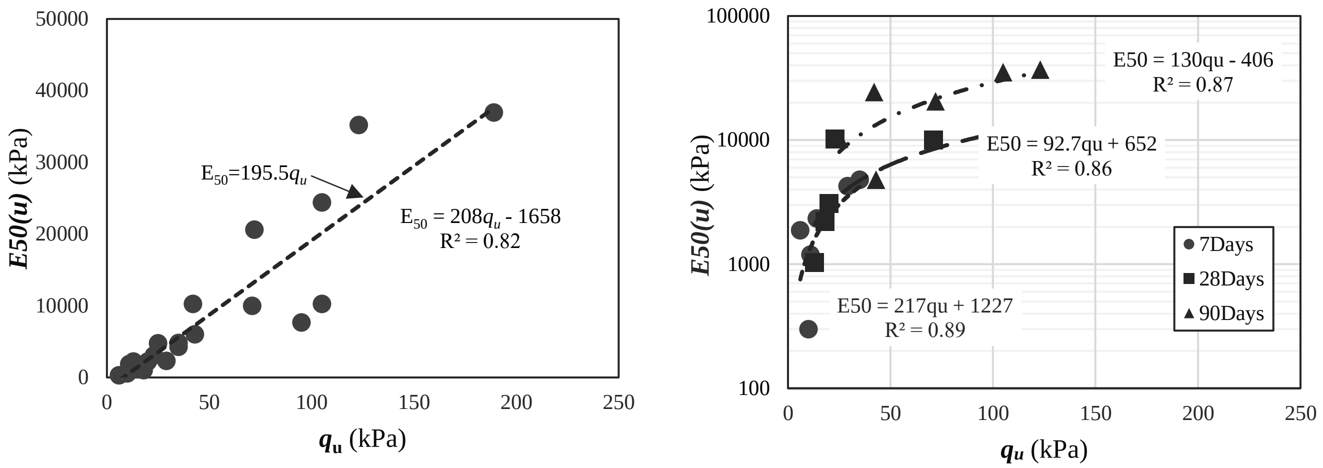
3.2.1 Stiffness Parameters

The stiffness characteristics of the proposed mixtures are represented by $E_{50(u)}$, the secant modulus of elasticity at 50% of deviator stress at failure (undrained). The stiffness determined from the UCS tests is the secant Young's modulus at 50% of the maximum shear stress. $E_{50(u)}$ is the secant modulus of elasticity at 50% of deviator stress at failure (undrained). It can be seen from Figure 3 that amended mixtures give a higher $E_{50(u)}$ value compared to untreated samples. The maximum value of $E_{50(u)} \approx 37000$ kPa is observed at C45-S50-L5, including B9% in batch slurry. The relationship of $E_{50(u)}$ against qu is shown in Figure 4. The plot of $E_{50(u)}$ versus unconfined compressive strength for powdered steel slag specimens is given in Figure 4(a). $E_{50(u)}$ values increase as qu increases and are in the soft-to medium-consistency range Figure 4(b). By using of curve fitting technique, a linear function of $E_{50(u)} = 195.5\, qu$, is founded to define the correlation of $E_{50(u)}$ vs. *qu*.



	B5-C100-S0	B5-C80-S20	B5-C50-S50	B5-C20-S80	B5-C50-S45-L5	B5-C45-S50-L5	B9-C50-S45-L5	B9-C45-S50-L5
■ 7Days	13150	4812	599	300	1882	1198	2338	4276
☰ 28Days	15603	10020	2218	1039	2224	3098	10264	7698
▩ 90Days	0	20631	6038	4790	10265	24440	35224	36953

Figure 3. Effect of curing ages on $E_{50(u)}$ values.



(a) **(b)**

Figure 4. Relationship between E_{50} and unconfined compressive strength (*qu*).

4. CONCLUSION

This paper presents a laboratory investigation into the workability (slump), permeability, and unconfined compression of powdered steel-slag, lime-amended, cement-bentonite backfills. The following conclusions were derived from this experimental research:

Powdered steel slag mixtures gave acceptable permeability values in 28 days of curing time. Mixture having 9% bentonite content, gave lower permeability at 90 days.

$E_{50(u)}$ values increased as qu increased and were in the soft-to medium-consistency range. For the 90-day curing period, the $E_{50(u)}$ value was in the medium consistency range (35-37 MPa). For designed mixtures, the secant modulus $E_{50(u)}$ values are 196-287 times greater than compressive strength. The enhancement of secant modulus has a suitable agreement with strength test results along with a linear function of $E_{50(u)}$ = 195.5 qu and correlation coefficient of R2 = 0.82.

The laboratory observations clearly show that the cement-bentonite-slag (CBS) backfill evaluated in this study strengthens with time. When placed, the backfill is a viscous liquid; later, it is material strong enough to stand vertically.

Overall, the laboratory tests result reveal that significant improvements to the properties of CB slurry can be made by adding powdered steel slag and lime. Thus, a mixture of powdered steel slag and lime is suggested to improve the engineering characteristics of CB slurry wall as amended mixtures with 9% of bentonite illustrate better engineering value (i.e., B9-C50-S45-L5 and B9-C45-S50-L5, Mixtures).

The above study has shown that the powdered steel slag can be used in slurry wall construction as an additive, and the use of powdered steel slag in the CB slurry wall eliminates the storage costs of steel slag and the amount of cement needed in CB slurry wall construction is reduced by 50%. Moreover, the steel slag utilization as an additive should be given precedence from environmental protection and economic perspective consideration.

REFERENCES

Andreas, L., Herrmann, I., Lidstrom-Larrsson, M., Lagerkvist, A. (2005). Physical properties of steel slag to be reused in a landfill cover. In *Proceedings Sardinia*.

ASTM Standard C188-09 (2009). Standard Test Method for Density of Hydraulic Cement. Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.

ASTM, Standard D2166-06 (2006). Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. ASTM International,West Conshohocken, PA.

ASTM, Standard D4318-05 (2010). Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International, West Conshohocken, PA.

ASTM, Standard D5084-03 (2010). Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a FlexibleWall Permeameter. ASTM International,West Conshohocken, PA. Germany,pp. 1323–1328, June.

ASTM D854-10 (2010). Standard test methods for specific gravity of soil. American Society for Testing of Materials, Pennsylvania, PA, USA.

Carreto, J. (2014). Self-hardening slurry walls. A contribution for design, quality control and performance monitoring (Doctoral dissertation, *Ph. D. thesis*, Dept. of Civil Engineering and Architecture from IST, Lisbon Univ., Lisbon, Portugal).

Carreto, J., Caldeira, L., and Maranha das Neves, E. (2015). Hydromechanical characterization of cement-bentonite slurries in the context of cut-off wall applications. J. Mater. Civ. Eng., 10.1061/(ASCE)MT.1943-5533.0001365, 04015093.

D'Appolonia, D. J. (1980). Soil-bentonite slurry trench cutoffs. *Journal of the Geotechnical Engineering Division*, *106*(4), 399-417.

Dhoble, Y. & Ahmed, S. (2018). Study on Cementitious Properties of Steel Slag by Partial Replacement of Cement. *Global Journal of Engineering Science and Researches*, *5*(7), 213-220.

Du, Y. J., Fan, R. D., Liu, S. Y., Reddy, K. R., Jin, F. (2015). Workability, compressibility and hydraulic conductivity of zeolite-amended clayey soil/calcium-bentonite backfills for slurry-trench cutoff walls. *Engineering Geology*, *195*, 258-268.

Evans, J. C. & Dawson, A. R. (1999). Slurry walls for control of contaminant migration: A comparison of UK and US practices. In *Geo-Engineering for Underground Facilities*, pp. 105-120.

Filz, G. M. (1996). Consolidation stresses in soil-bentonite backfilled trenches. In *Environmental Geotechnics*, pp. 497-502.

ICE (Institution of Civil Engineers). (1999). Specification for the construction of slurry trench cut-off walls as barriers to pollution migration.

Jefferis, S. A. (2008). Reactive transport in cut-off walls and implications for wall durability. In *GeoCongress 2008: Geotechnics of Waste Management and Remediation*, pp. 652-659.

Joshi, K., Kechavarzi, C., Sutherland, K., Ng, M. Y. A., Soga, K., Tedd, P. (2010). Laboratory and in situ tests for long-term hydraulic conductivity of a cement-bentonite cutoff wall. *Journal of geotechnical and geoenvironmental engineering*, *136*(4), 562-572.

Khajeh, A., Jamshidi Chenari, R., Payan, M. (2020). A simple review of cemented non-conventional materials: soil composites. *Geotechnical and Geological Engineering, 38*(2), 1019-1040.

LaGrega, M. D., Buckingham, P. L., Evans, J. C. (2001). Hazard waste management, 2nd edn. McGraw-Hall. *Inc., New York*.

Manassero, M., Fratalocchi, E., Pasqualini, E., Spanna, C., Verga, F. (1995). Containment with vertical cutoff walls. In *Geoenvironment: Characterization, Containment, Remediation, and Performance in Environmental Geotechnics*, pp. 1142-1172.

B. Mason. (1944). The constitution of some basic open-hearth slags, J. Iron Steel Inst, 150, pp. 69-80.

Millet, R. A. & Perez, J. Y. (1981). Current USA practices: Slurry wall specifications. *Journal of the Geotechnical Engineering Division, 107*(8), 1041-1056.

Opdyke, S. M. & Evans, J. C. (2005). Slag-cement-bentonite slurry walls. *Journal of geotechnical and geoenvironmental Engineering, 131*(6), 673-681.

Oweis, IS, Khera, RP (1990): Geotechnology of WasteManagement. Butterworth-Heineman: Oxford, UK

Portland Cement Association (PCA), (2005). “Iron and Steel Byproducts: Portland Cement Association Sustainable Manufacturing Fact Sheet.” http://www.cement.org/pdf_files/is326.pdf

Ruffing, D. G., Evans, J. C., Malusis, M. A. (2010). Prediction of earth pressures in soil-bentonite cutoff walls. In *GeoFlorida 2010: Advances in Analysis, Modeling & Design*, pp. 2416-2425.

Bodocsi, A., Rumer, R. R., & Ryan, M. E. (Eds.). (1995). Barrier containment technologies for environmental remediation applications.

Ryan, C. R. (1987), Vertical barriers in soil for pollution containment, Geotechnical Practice for Waste Disposal, ASCE, New York, 182-204.

Shi, C. (2004). Steel slag—its production, processing, characteristics, and cementitious properties. *Journal of materials in civil engineering, 16*(3), 230-236.

Slag-Cement-Bentonite Slurry Walls Geo-Solutions: Soil and Groundwater Problems Solved. Geo. (2017). www.geo-solutions.com/services/slurry-walls/slag-cement-cement-bentonite.

Spooner, P. A., Wetzel, R. S., Spooner, C. E., Furman, C. A., Tokarski, E. F. (1984). *Slurry trench construction for pollution migration control. 82-20* (No. PB-84-177831). JRB Associates, Inc., McLean, VA (USA).

Sreedharan, V., & Puvvadi, S. (2013). Compressibility behaviour of bentonite and organically modified bentonite slurry. *Géotechnique, 63*(10), 876-879.

Talefirouz, D., Çokça, E., Omer, J. (2016). Use of granulated blast furnace slag and lime in cement-bentonite slurry wall construction. *International journal of geotechnical engineering, 10*(1), 81-85.

TSPA. (2015). Iron Steel Slag Report, Turkey Steel Producers Association.

Wang, D., Zentar, R., Abriak, N. E. (2018). Durability and swelling of solidified/stabilized dredged marine soils with class-F fly ash, cement, and lime. *Journal of Materials in Civil Engineering, 30*(3), 04018013.

Wang, Q., Yang, J., Yan, P. (2013). Cementitious propertiess of super-fine steel slag. *Powder technology, 245*, 35-39.

Xu, H., Zhu, W., Qian, X., Wang, S., Fan, X. (2016). Studies on hydraulic conductivity and compressibility of backfills for soil-bentonite cutoff walls. *Applied Clay Science, 132*, 326-335.

Talefirouz, D. & Çokça, E. (2021). Use of Powdered Steel Slag in Cement-Bentonite Slurry Wall Construction. *Sirnak University Journal of Sciences, 2*(2), 1-15.

Talefirouz, D. & Çokça, E. (2021). Çimento-Bentonit Bulamaç Duvar İnşaatında Toz Çelik Cüruf Kullanımı. *Şırnak Üniversitesi Fen Bilimleri Dergisi, 2*(2):1-15.