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Fresh and hardened concrete properties containing red mud and silica fume

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Original research paper

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In recent years, various studies have been conducted on the utilisation of bauxite residue from alumina production (known as red mud) in the construction industry. It is particularly noteworthy as a partial replacement for cement in concrete because of its favourable chemical composition. In this study, red mud and silica fume were investigated as partial replacements for cement in concrete. Five mixtures were tested. Herein, cement was replaced with red mud at 0, 5, 10, 15 and 20 % by cement mass. Furthermore, cement was replaced by silica fume at 10 % by cement mass in all the mixtures. The workability, bulk density, and air content were tested to evaluate the properties of the fresh concrete. The bulk density, water absorption, compressive strength, splitting tensile strength, water penetration, and freeze–thaw resistance were tested to evaluate the properties of the hardened concrete. The results indicated that for a low red mud content, reasonable fresh and hardened concrete properties were achieved.

Key words:

concrete, red mud, silica fume, hardened properties, durability

Izvorni znanstveni rad

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Svojstva svježeg i očvrsnulog betona s dodatkom crvenog mulja i silicijske prašine

U posljednjih nekoliko godina proveden je određeni broj istraživanja o korištenju ostataka boksita iz proizvodnje aluminija (poznatog kao crveni mulj) u građevinskoj industriji. Zbog svojih povoljnih kemijskih svojstava, ovaj materijal posebno je zanimljiv kao djelomična zamjena cementa u betonu. U ovom su istraživanju proučavani crveni mulj i silicijska prašina kao djelomične zamjene cementa u betonu. Ispitano je pet mješavina u kojima je cement zamijenjen s 0, 5, 10, 15 i 20 % crvenog mulja. Osim toga, u svim mješavinama cement je zamijenjen s 10 % silicijske prašine u odnosu na masu cementa. Da bi se odredila svojstva svježeg betona, ispitani su obradivost, gustoća i udio zraka. U očvrsnulom stanju ispitani su gustoća, upijanje vode, tlačna čvrstoća, vlačna čvrstoća cijepanjem, prodor vode i otpornost na smrzavanje i odmrzavanje. Rezultati su pokazali da se kod betona s manjom količinom crvenog mulja dobivaju zadovoljavajuća svojstva u svježem i očvrsnulom stanju.

Ključne riječi:

beton, crveni mulj, silicijska prašina, svojstva očvrsnulog betona, trajnost

1. Introduction

Over the past years, concrete has been one of the most commonly used building materials worldwide, with its annual production exceeding 10 billion tons [1]. A large amount of natural non-renewable raw materials is used in the production process of concrete and its components. In addition, substantial emissions of gases, primarily CO_2, occur. The industrial cement production is at the forefront, accounting for approximately 8 % of the total CO_2 emissions in the atmosphere [2]. Meanwhile, the construction industry accounts for approximately 38 % [3]. In 2019, 4.1 billion tons of cement was produced. The leading countries were China (56,2 %), India (7,8 %), and the United States (2,2 %) [4]. In [5], such an expansion in cement production was not anticipated until 2050. The impact of concrete on the environment is significant. Efforts are being undertaken to reduce it in terms of natural resource conservation and emission reduction. Cement production and consumption are the focus because these account for 96 % of the carbon footprint of concrete and 85 % of the installed energy [6]. Therefore, the strategy of the construction industry is to reduce the use of cement or replace it with other materials (supplementary cementitious materials) [7].

One of the prevailing concepts is to use industrial by-products from other industries as raw materials for cement production or to replace cement in composites [8, 9]. These materials are considered waste and are not used further in the industry. The validation for their application in cement production or as a cement replacement lies in their chemical composition and particle sizes [10]. Certain by-products such as silica fume, fly ash, and slag are being used in the cement industry or as additives in concrete. In recent years, new materials that can be used as partial replacements for cement have been studied, such as red mud [11, 12].

Red mud is a by-product of the industrial production of alumina from bauxite ore [13]. Approximately 0,3–2,5 tons of red mud is generated in the production of 1 ton of alumina [12]. In 2019, the aluminium production attained 63,7 million tons [14]. This implies that over 120 million tons of red mud is generated annually [15]. The identifiable red colour originates from the high iron content. Its chemical composition includes aluminium, sodium, titanium, calcium, and silicon oxides. Depending on the origin of the bauxite ore and the alumina production process, the chemical composition varies considerably. The average contents of the main oxides are as follows [16]: aluminium oxide 6–28 %, iron oxide 12–56 %, silicon oxide 2–25 %, titanium oxide 2–28 %, and calcium oxide 0,20–4 %.

The average pH of red mud is 10–12,5, and its particle size is less than 10 μm [11]. Red mud has attracted the attention of researchers because of its chemical composition and particle size. It cannot be fully considered an artificial pozzolan. However, its pozzolanic activity index is good and can be increased by calcination [17-19]. The alkaline character is compatible with the cement matrix. For the active formation of C-S-H gel, the pH should be higher than 11,5 [18, 20]. If the pH is lower than 9,5, hydration would not occur.

Earlier, red mud was investigated as a raw material for cement production [11, 21-24]. In recent years, it has been studied intensively as a partial cement replacement in composite materials. The effects of the addition of red mud on the workability, hardened properties, and durability of concrete and mortar were evaluated. Most studies reported reduced workability of the mixtures owing to the small particle size of red mud compared with that of cement, which increases the need for water [17, 25]. A study [26] demonstrated that a low percentage of cement substitution with red mud (up to 15 %) affects a marginal increase in the compressive strength. Meanwhile, [27] demonstrated that the addition of 10 % of red mud to concrete affects the increase in compressive strength by 12 % and tensile strength by 19 %. The compressive and flexural strengths of concrete were evaluated in [28]. The results indicated a small decrease of 3 % for low red mud addition (up to 10 %). However, for 20 % red mud addition, both compressive and flexural strengths decreased significantly (by approximately 40 %). However, it has been reported that the addition of red mud may have a positive impact on the durability of concrete. Red mud addition affects the chloride diffusion reduction [29] and reinforcement corrosion potential reduction [30]. That is, a longer lifespan of concrete is likely with red mud. The durability properties of concrete with red mud were also presented in [31]. The results indicated an increased autogenous shrinkage but a decreased drying shrinkage. In addition, a low chloride migration coefficient and high electrical resistance were observed.

As stated earlier, the chemical composition of red mud varies. In Figure 1, the distribution of the main oxides (SiO_2-Fe_2O_3-CaO and SiO_2-Al_2O_3-CaO) in red mud determined by previous research is presented as a ternary diagram [17 - 37]. A relatively low CaO content is observed, with a high Fe_2O_3 content in most cases. The Al_2O_3 and SiO_2 contents vary significantly.

Many researchers have recommended the application of other materials with red mud as a replacement for cement to maximise its effects on concrete properties [28, 31-37].

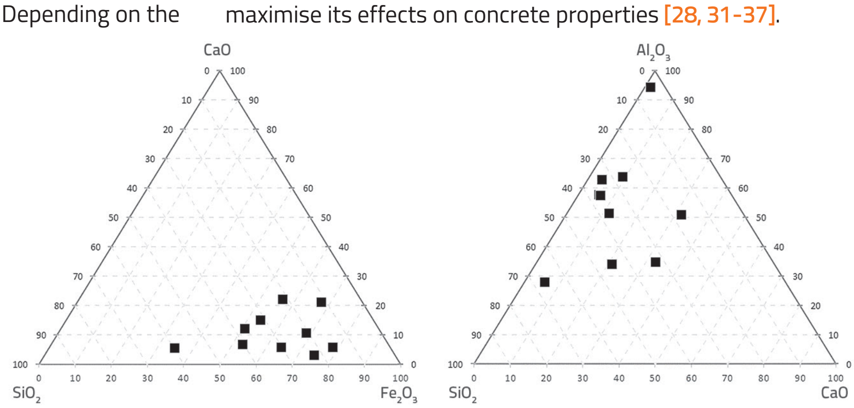

Figure 1. Ternary diagram of SiO_2-Fe_2O_3-CaO and SiO_2-Al_2O_3-CaO in red mud

Table 1. Sieve analysis

Sieve size [mm]	0.125	0.25	0.5	1	2	4	8	16
Passing [%]	2.52	4.57	12.22	22.51	34.41	48.68	67.52	100

Table 2. Chemical composition of the red mud from Dobro Selo

Oxide	Al_2O_3	Fe_2O_3	Na_2O	CaO	SiO_2	MgO	K_2O	MnO	TiO_2	SO_3
Content [%]	16.46	37.85	2.39	10.41	21.79	0.60	0.20	0.59	1.64	0.20

Silica fumes are acknowledged in the construction industry as highly reactive pozzolan [38]. It is composed mostly of SiO_2 (≥ 85 %) and has a specific surface area of approximately 150000 cm^2/g. When added to concrete, it increases its strength (the mechanical properties in general), abrasion resistance, resistance to chemical agents, and corrosion, and reduces its water penetration [2]. A pozzolanic reaction in concrete occurs between silica fume and calcium hydroxide (CH). This produces additional C-S-H in the pores around the hydrated cement. Because of its large specific surface area, additional water is required for concrete [2].
Therefore, in this study, the properties of fresh and hardened concrete were investigated after partially replacing cement with red mud and silica fume. Five mixtures were tested. Cement was replaced by red mud at 0 %, 5 %, 10 %, 15 %, and 20 % by cement mass, whereas silica fume replaced cement by 10 % of cement mass in all the mixtures. The properties were presented based on the percentage of red mud added. Special attention was paid to the durability properties of concrete because there is limited research on this area.

2. Materials

2.1. Cement and aggregate

In this work, 42,5 MPa-strength cement was used (labelled as Portland cement CEM II/A-M (S-V) 42,5N), with 20 % addition of slag and fly ash. The cement was prepared in accordance with EN 197-1, with a specific gravity of 3,05 g/cm^3 and specific surface area of 2900 cm^2/g. Crush-separated limestone was used as the aggregate. The aggregates comprised three nominal fractions: 0–4 mm (45 %), 4–8 mm (20 %), and 8–16 mm (35 %). The average specific gravity was 2,7 g/cm^3. The results of the sieve analysis are presented in Table 1. The fineness modulus was 5,08.

2.2. Red mud

Red mud was obtained from the Dobro Selo landfill near Mostar, Bosnia, and Herzegovina. The material is a residue of alumina produced from bauxite ore from the Herzegovina region and was generated in 1979–1991. It is estimated that nearly 10 million tons were deposited in the Dobro Selo landfill during the production process. The landfill consists of two reinforced concrete pools, in which red mud is covered with a layer of water. Production ceased in 1991. Since then, landfills have become inactive [13]. The chemical analysis results of red mud is presented in Table 2. It has a high pozzolanic oxide content (aluminium, iron, and silicon oxides) and low content of sodium and magnesium oxides. Both the oxides are considered hazardous when used in cement matrices. The sodium oxide equivalent (Na_2Oeq) should be lower than 5 % according to EN 450:1, and the magnesium oxide equivalent should be lower than 4 % [1]. Na2Oeq was calculated as follows:

$$Na_2Oeq = Na_2O + 0{,}658K_2O = 2{,}52\ \% \quad (1)$$

Radioactivity measurements did not reveal a significant radioactivity level [13]. The sum of pozzolanic oxides was higher than 70 % and that of SO_3 was less than 3 % (according to EN 450:1). According to ASTM C618, red mud satisfies the criteria for class F fly ash with a CaO content lower than 18 %. In addition, the presence of TiO_2 can affect the properties of concrete [39].
Red mud samples were delivered with a high water content. Red mud was first dried, ground into a fine powder, and added to the concrete mixtures. The specific gravity of the red mud was tested using a pycnometer and was determined to be 3,15 g/cm^2. The bulk density was 1,35 g/cm^3. The specific surface area was tested according to EN 196-6 by the Blaine method and determined to be 8300 cm^2/g. This implies that red mud particles are approximately three times smaller than cement particles.
In [40], the rare-element content in the red mud from the Dobro Selo landfill was presented. All the lanthanides as well as Sc and Y were observed to be present. Ce is the most abundant element. A chemical analysis revealed the Al_2O_3 Fe_2O_3, CaO, and SiO_2 contents to be approximately 15 %, 50 %, 3 %, and ≥ 15 %, respectively. In addition, the analysis revealed the presence of Cr, Hg, Ni, V, and Zn.

2.3. Silica fume

Silica fumes were obtained from Jajce, Bosnia, and Herzegovina. This waste material is used to produce Si alloys. Approximately 10.000 tons of silica fume is generated annually during the production process. The particle size of silica fume is 0,1–0,2 μm, i.e., it is approximately 100 times finer than cement. Silica fume was used as the liquid phase with 56 % water content.

3. Experimental plan

Table 3 shows the concrete mix proportions. Five mixtures were made by partial cement replacement with red mud and silica

Table 3. Concrete mixture proportion

Mix	Cement [kg/m³]	Silica fume		Red mud		Total binder [kg/m³]	Aggregate [kg/m³]	Water [kg/m³]	w/c ratio	w/b ratio
		[%]	[kg/m³]	[%]	[kg/m³]					
B1	324	10	36	0	0	360	1750	244.8	0.756	0.68
B2	306	10	36	5	18	360	1750	244.8	0.800	0.68
B3	288	10	36	10	36	360	1750	244.8	0.850	0.68
B4	270	10	36	15	54	360	1750	244.8	0.907	0.68
B5	252	10	36	20	72	360	1750	244.8	0.971	0.68
v/c – vodocementni omjer; v/v – vodovezivni omjer										

Table 4. Test methods and number of samples

Test methods	Number of samples per test	Shape/dimension	Total number of samples
28 day compressive strength	3	Cube, 15 cm	15
56 day compressive strength	3	Cube, 15 cm	15
90 day compressive strength	3	Cube, 15 cm	15
Splitting tensile strength / Water penetration	3	Cylinder Ø15/15 cm	15
Freeze–thaw resistance	2	Cube, 15 cm	10

fume. Red mud was added at 0 %, 5 %, 10 %, 15 %, and 20 % by cement mass, and silica fume replaced cement to 10 % by cement mass in all the mixtures. Thus, cement, red mud, and silica fume were considered as a biner. The mixture without red mud was the reference mixture. The workability, bulk density, and air content were tested to evaluate the fresh concrete properties. The bulk density; water absorption; compressive strength at 28, 56, and 90 days of age; splitting tensile strength; water penetration; and freeze–thaw resistance were tested to evaluate the hardened concrete properties.

The water / binder ratio (w/b) was maintained constant at 0,68, whereas the water / cement ratio (w/c) varied. The mixture B1 was considered as the reference. All the comparisons were made with respect to that mixture.

It should also be noted that blended cement was used with 20 % slag and fly ash. The reference mixture was composed of 72 % clinker, 18 % slag and fly ash, and 10 % silica fume. The content of clinker in the other mixtures was lowered by the addition of red mud. The mixtures B2, B3, and B4 contained 68 %, 64 %, and 60 % clinker, respectively. For B5, the contents of clinker, slag and fly ash, silica fume, and red mud were 56 %, 14 %, 10 %, and 20 %.

Totally 70 samples were prepared for the hardened property tests: 55 cubes of 15 × 15 × 15 cm and 15 cylinders with a diameter of 15 cm and height of 15 cm. All the samples were kept in moulds for a minimum of 24 h, demoulded, and cured in a water tank until testing. Table 4 lists the test methods and the number of samples for each test.

3.1. Fresh concrete properties tests

The workability, bulk density, and air content of fresh concrete were tested. A slump test was conducted to determine the workability of the mixtures according to EN 12350-2. The air content was determined according to EN 1992-1-1:2017 by the pressure method.

3.2. Hardened concrete property tests

The hardened concrete properties were determined by evaluating the bulk density, water absorption, compressive strength, splitting tensile strength, water penetration, and freeze–thaw resistance with a sodium chloride solution.

The water absorption was tested by exposing the samples to complete saturation after curing, followed by drying to a constant weight. Twelve samples were tested in this study.

The compressive strength was tested at 28, 56, and 90 days of age. The compressive strength was tested on cubic samples (15 × 15 × 15 cm) using the EN 12390-3:2010 standard. The splitting tensile strength was tested on cylindrical samples with a diameter of 15 cm and height of 15 cm according to EN 12390-6:2010. The water penetration was evaluated using EN 12390-8:2010 on three cylindrical samples with a diameter of 15 cm and height of 15 cm. The samples were then immersed in water at a pressure of 5 bar for 72 h. Subsequently, the samples were halved, and the depth of water penetration was measured. After the test, the water penetration coefficient was calculated by Equation (2) [2]:

$$K_w = \frac{\omega_0}{2 \cdot P \cdot t} dm^2 \qquad (2)$$

ω_0 - water density [N/mm³]
P - water pressure [MPa]
t - time under pressure [h]
dm - water penetration depth [mm].

Table 5. Fresh concrete test results

Mix	Slump [cm]	Increase/ Decrease [%]	Air content [%]	Increase/ Decrease [%]	Bulk density [kg/m³]	Increase/ Decrease [%]
B1	18.0	-	1.10	-	2343.75	-
B2	17.5	-2.78	0.70	-36.36	2350.00	+0.27
B3	14.0	-22.22	1.30	+18.18	2307.50	-1.55
B4	8.0	-55.56	1.40	+27.27	2336.25	-0.32
B5	4.0	-77.78	2.00	+81.82	2318.75	-1.07

Slika 2. Ispitivanje obradivosti betonskih mješavina B1-B5 (slijeva nadesno)

The freeze–thaw resistance with a sodium chloride solution was tested in accordance with CEN/TS 12390-9:2007. The freeze–thaw resistance was tested on cube samples that were cut in half. The inner sides were sealed on the edges with steel rings, and a 3 % sodium chloride solution was added. Then, the samples were exposed to 28 frost–thaw cycles with a minimum temperature of -20 °C and maximum temperature of 20 °C. The freeze–thaw resistance with a sodium chloride solution is one of the most rigorous tests for concrete durability. The freeze–thaw resistance is the most critical durability property of concrete, particularly in cold regions. Because freeze–thaw with a sodium chloride solution is more rigorous, it was selected for this test. The cumulative residues of the individual samples were gathered from the material that broke off during the test procedure and weighed. The mass loss, S_n, was calculated using Equation (3):

$$S_n = \frac{m_{s,n}}{A} \qquad (3)$$

$m_{s,n}$ - cumulative residue after n cycles [kg]
A - total test area [m²].

4. Results and discussion

4.1. Properties of fresh concrete

Table 5 presents the workability, air content, and bulk density results for the fresh concrete. Furthermore, the results were compared with those of B1.

The addition of red mud significantly affected the concrete properties in the fresh state. The measured slumps for all the concrete mixtures with red mud were lower than that of the reference mix. The workability decreased with an increase in the addition of red mud, which was registered for a small amount of 5 %. This was owing to the fineness of the red mud particles. These are smaller than cement particles and retain part of the water and thereby, degrade the fluidity of concrete by absorbing water [25, 31]. B2 had the lowest registered air content of 0,70 %, which is 36,36 % lower than that of the reference mix. All the other mixtures had an air content higher than that of B1. A small amount of red mud (up to 5 %) helped reduce the air content. However, when the red mud content was increased, the air content also increased. The bulk density in the fresh state was largely uniform, with B2 showing a marginally higher measured bulk density of 2350,00 kg/m³. This was 0,27 % higher than that of the reference mixture B1. Smaller and heavier red mud particles increased the bulk density and decreased the air content. However, because the workability was reduced, the quality of concrete installation was low. Thus, for high red mud additions, the concrete mixtures displayed an increased air content and a decreased bulk density. A similar behaviour was observed in [41]. The workability tests for all the concrete mixtures are presented in Figure 2.

4.2. Properties of hardened concrete

4.2.1. Bulk density, absorption, and water penetration

The samples were cured in water for 28 days. Then, these were measured and weighed. Table 6 presents the results for the hardened bulk density, absorption, and water penetration. These were compared with those of the reference mix B1.

Table 6. Bulk density, absorption, and water penetration test results

Mix	B1	B2	B3	B4	B5
Bulk density [kg/m³]	2333.80	2340.40	2335.10	2337.30	2330.80
Increase/Decrease [%]	-	+0.28	+0.06	+0.15	-0.13
Absorption [%]	1.29	1.20	1.27	1.34	1.74
Increase/Decrease [%]	-	-7.15	-1.23	+4.11	+35.04
Water penetration coefficient [mm/h]	2.08×10^{-5}	4.74×10^{-5}	6.44×10^{-5}	3.49×10^{-5}	1.79×10^{-3}

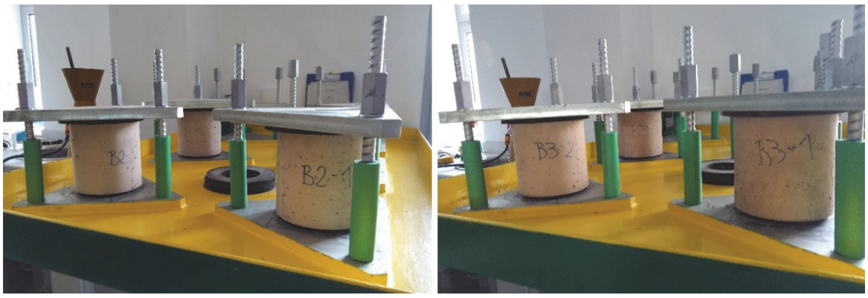

Figure 3. Water penetration test procedure (mixtures B2 and B3)

The mixtures B2, B3, and B4 showed a marginal increase in the bulk density, whereas B5 showed a decrease of 0,13 % compared with the reference mix. A red mud addition of 5–5 % resulted in an increase in the bulk density of cement because of its fineness and density. However, a high red mud content decreased the bulk density owing to the low workability. B2 had the lowest water absorption of 1,20 %, i.e., a 7,15 % decrease compared with the reference mix. B3 had a similar absorption as the reference mix, whereas B4 and B5 had the highest absorptions of 1,34 % and 1,74 %, respectively. At small percentages, red mud affected the reduction of pores in concrete and thereby, reduced the absorption. However, as the red mud content increased, it hindered the correct installation of concrete. This, in turn, resulted in an increase in porosity [34]. The results of the water penetration test are presented using the water penetration coefficient (WPC). The test procedure is illustrated in Figure 3. B1 had the lowest WPC and therefore, the lowest penetration of water in the specimen. B2 and B4 had reasonable WPCs, and B5 had the highest water penetration of 120,3 mm. The results indicate that for a low red mud content, concrete behaves reasonably. However, an increase in the proportion of red mud to a value above 15 % results in a stiff mixture with a high potential for water absorption and retention.

4.2.2. Splitting tensile strength

The results for splitting tensile strength are presented in Figure 4. As shown in Figure 3, the splitting tensile strengths of B3 and B4 increased by 13,16 % and 19,25 %, respectively, compared with that of the reference mix. B2 and B5 exhibited a decrease of 11,72 % and 19,27 %, respectively. An increase in the splitting tensile strength with an increase in red mud was reported in [34, 42]. The alkaline characteristic of red mud could have caused the increase in the splitting tensile strength of B3 and B4, which enhances the formation of C–S–H gels [32]. Meanwhile, a high red mud content causes a decrease in the splitting tensile strength. However, the low presence of red mud affects the reduction of microcracks and thereby, causes an increase in the splitting tensile strength [43].

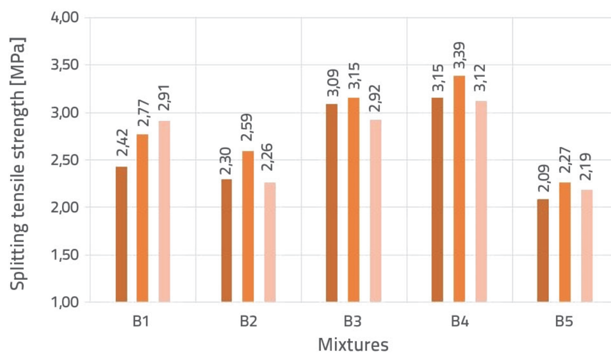

Figure 4. Splitting tensile strength results

4.2.3. Compressive strength

The compressive strength test results at 28, 56, and 90 days of age for B1–B5 are presented in Figure 5. The results for B1 are listed in Table 7.

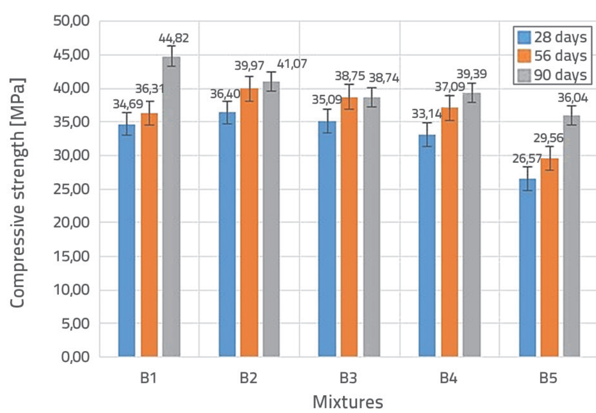

Figure 5. Compressive strength test results with average values for 28, 56, and 90 days of age

Table 7. Level of increase/decrease in compressive strength compared with reference mix B1

Compressive strength test age	B2	B3	B4	B5
28 days	4.94	1.15	-4.47	-23.41
56 days	10.07	6.71	2.14	-18.16
90 days	-4.85	-10.24	-8.74	-16.50

Table 8. Test results for freeze–thaw resistance with sodium chloride solution

Mix	Residue after 7 days	Residue after 14 days	Residue after 28 days	Cumulative residue [kg]	Mass loss Sn [kg/cm^2]	Average mass loss S_n [kg/cm^2]	No of cycles
B1	0.0028	0.0046	0.0039	0.0113	0.58	0.35	28
	0.00069	0.00077	0.00094	0.0024	0.12		28
B2	0.0016	0.0013	0.0021	0.0050	0.26	0.47	28
	0.0036	0.0043	0.0056	0.0135	0.69		28
B3	0.0031	0.0047	-	0.0078	0.40	0.86	14
	0.0037	0.0087	0.0135	0.0259	1.32		28
B4	0.0054	0.0042	-	0.0096	0.49	0.69	14
	0.0084	0.0092	-	0.0176	0.90		14
B5	0.0035	0.0045	-	0.0080	0.41	0.54	14
	0.0068	0.0062	-	0.0130	0.66		14

The effect of the addition of red mud on the development of compressive strength was considered through the compressive strength test results for 28, 56, and 90 days of aging. All the mixtures exhibited an increase in the compressive strength with an increase in the age. This was anticipated. At 28 days of age, B2 and B3 showed increases in the compressive strength by 4,94 % and 1,15 %, respectively, compared with the reference mix. However, B4 and B5 showed decreases of 4,47 % and 23,41 %, respectively. Red mud additions at small percentages of 5 % and 10 % caused a marginal increase in the compressive strength for the specimens aged 28 days. This is in line with [27]. The increase in the compressive strength can be attributed to the alkaline characteristic of red mud, which contributes to the pozzolanic reactivity that accelerates C–S–H gel formation [34]. At 56 days of age, an increase in the compressive strength was observed for B2, B3, and B4. Compared with the reference mix, B2, B3, and B4 showed increases of 10,07 %, 6,71 %, and 2,14 %, respectively. B5 showed a decrease in compressive strength of 18,60 %. In this phase, red mud still contributed to the increase in compressive strength, similar to the cases of the samples aged 28 days. The compressive strength test results after 90 days of aging showed different patterns. The mixtures with red mud (B2, B3, B4, and B5) exhibited a decrease in compressive strength compared with the reference mix. B2 showed the highest results among the four mixes, with a decrease of 4,85 %. B3, B4, and B5 exhibited compressive strengths of 10,24 %, 8,74 %, and 16,50 %, respectively. The B5 samples had the lowest compressive strength for all the tested periods (28, 56, and 90 days). For a high red mud content, the material had an insufficient pozzolanic reaction with other minerals. This resulted in a reduction in calcium silicate hydrate (C–S–H) gel formation [34] and thereby, a reduction in the compressive strength.

The test results indicated that for the development of the compressive strength, the optimal red mud content was up to 10 %. For this mixture, the strength was reasonable for the three tested time-intervals. The addition of silica fume should be considered. It played a key role in the development of the compressive strength of the B1 samples by reacting with free lime and creating an additional C–S–H gel [2]. The reaction also occurred naturally in the other samples (B2, B3, B4, and B5). However, because the amount of cement was reduced, it can be assumed that there was less $Ca(OH)_2$ in this reaction. In addition, a high amount of red mud caused an enhancement of the porosity and aggravated micromechanical properties. This eventually caused a decrease in the compressive strength [44]. The variations in the compressive strengths of all the mixtures are shown in Figure 4. Similar results have been reported earlier [34, 45-47].

4.2.4. Freeze–thaw resistance

The test results for freeze–thaw resistance with a sodium chloride solution are presented in Table 8. The test procedure is illustrated in Figure 6. The table lists the cumulative residue values for the individual mixtures. These were obtained by weighing the material that broke off during the test procedure. The mass loss S_n was calculated based on these results.
Table 7 shows that B1 and B2 endured all the 28 cycles, with average S_n values of 0,35 and 0,47 kg/cm^2, respectively. Although one sample of B3 endured 28 cycles, the other samples showed increased damage after 14 cycles. Therefore, these were not tested further. For B4 and B5, the destruction of the samples after 14 cycles was recorded. These were not tested further. The results

Figure 6. Freeze–thaw resistance with sodium chloride solution test procedure

indicate that with high levels of red mud, concrete is highly sensitive to freeze–thaw cycles with a sodium chloride solution. However, for a low red mud content, the results are reasonable. Similar tests are not available in the literature. However, the freeze–thaw resistance was presented in [13, 48, 49]. The results indicated that the presence of red mud contributes to the freeze–thaw resistance.

4.3. Effect of red mud on hardened concrete properties

A regression analysis was conducted to determine the strong relationships between the hardened concrete properties and red mud addition. Figures 7–9 show the relationship between the compressive strength for different sample ages and red mud addition. The compressive strengths at both 28 and 56 days can be represented by a second-order polynomial functions. The 28 day compressive strength is presented below:

$$CS = -517{,}63RM^2 + 66{,}332RM + 34{,}219, \quad R^2 = 0{,}9865 \tag{4}$$

The 56 day compressive strength is presented below:

$$CS = -646{,}9RM^2 + 96{,}968RM + 36{,}304, \quad R^2 = 0{,}9785 \tag{5}$$

The 90 day compressive strength can be represented by a linear function:

$$CS = -38{,}465RM + 43{,}857, \quad R^2 = 0{,}8811 \tag{6}$$

The absorption (A) can be linked to the water penetration because both the properties are affected by the concrete porosity. Water penetrates through the capillary pores in cement and through the porous interface of cement and large aggregates [2]. The relationship between the WPC and absorption is presented in Figure 10 through a linear regression analysis. Equation 7 shows the relationship between the WPC and absorption:

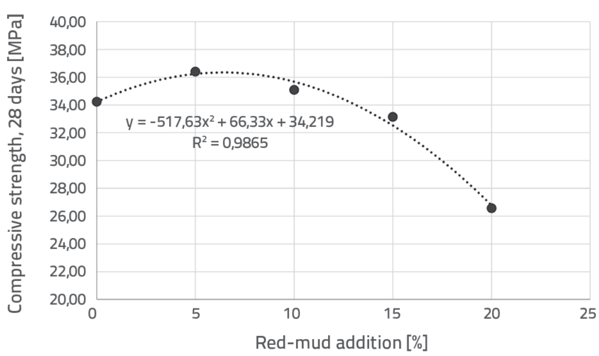

Figure 7. 28 day compressive strength vs. red mud addition

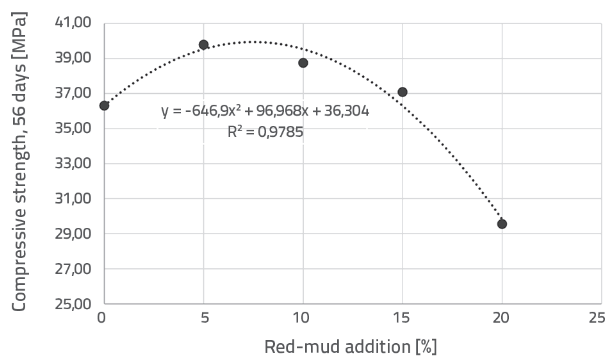

Figure 8. 56 day compressive strength vs. red mud addition

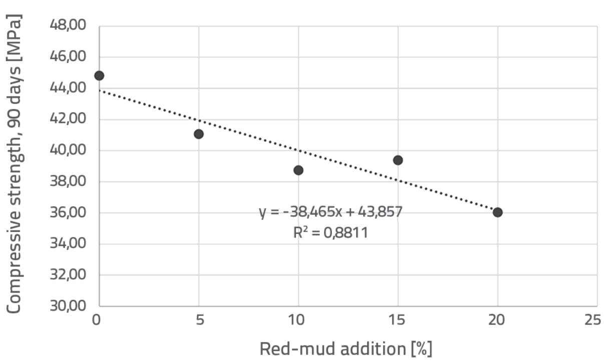

Figure 9. 90 day compressive strength vs. red mud addition

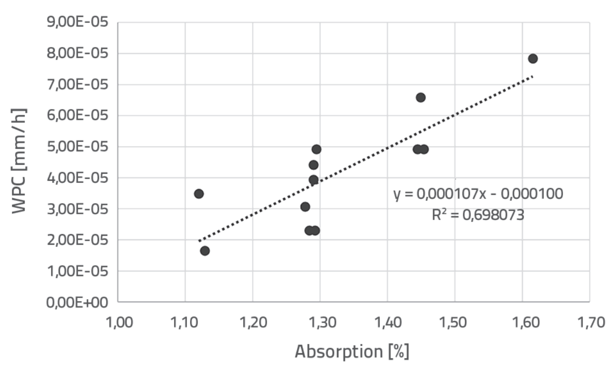

Figure 10. WPC vs. absorption

$$WPC = 0{,}000107A + 0{,}0001, \quad R^2 = 0{,}698 \tag{7}$$

The analysis of the relationship between the compressive strength and water absorption for concrete in the presence of red mud is also noteworthy. It was performed in [50]. In this study, a strong linear relationship between the compressive strength (28 days) and absorption was observed (Figure 11). It can be expressed as follows:

$$CS = -17{,}987A + 57{,}806, \; R^2 = 0{,}9944 \tag{8}$$

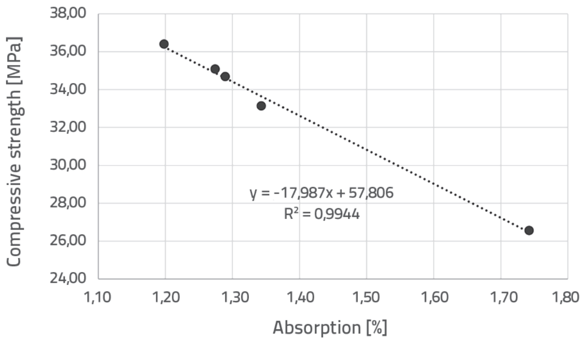

Figure 11. Compressive strength vs. absorption

5. Conclusion

This study included red mud and silica fume as partial replacements for cement in concrete. In previous research, red mud was mostly considered to be inert and to contribute marginally to concrete strength. Thus, the concept was to combine red mud with silica fume, which is a common supplementary cementitious material. The fresh, mechanical, and durability properties of the five mixtures with a partial replacement of the cement with red mud and silica fume were tested. Because blended cement was used with 80 % of clinker, the research could be considered as a synergy between cement, fly ash, slag, red mud, and silica fume. The following conclusions can be drawn based on the results:

- The workability of the mixtures decreased with an increase in the red mud content. The mixture with 0 % red mud had an 18 cm slump, whereas that with 20 % red mud had a 4 cm slump.
- The mixture with 5 % red mud had the lowest air content (0,70 %). The reference mixture had an air content of 1,1. Furthermore, the air content increased with an increase in the red mud percentage.
- The bulk density in the fresh state was largely uniform, with B2 showing a marginal increase of 0,27 % compared with the reference mixture.
- The mixture with 5 % red mud exhibited the lowest water absorption, which increased with the red mud content. Finer red mud particles retained water and thereby, increased the absorption of samples with high red mud content.
- The samples with 10 % and 15 % red mud contents had the highest split tensile strength. This can be attributed to the fineness of red mud.
- A small amount of red mud resulted in an increase in the compressive strength of concrete samples at 28 and 56 days compared with the reference mix. However, with a red mud content higher than 15 %, the compressive strength decreased significantly. At 90 days, the reference mix exhibited the highest compressive strength.
- In terms of durability, mixtures with 5 % and 10 % red mud content exhibited satisfactory WPC values. However, above this level, the water penetration was significant. The test results for freeze–thaw resistance with a sodium chloride solution showed that with the addition of red mud at above 10 %, the samples exhibited significant damage. For a low red mud content, the results were reasonable.

Concrete with a low red mud content and silica fume as common supplementary cementitious materials exhibited satisfactory fresh and hardened properties. It should be emphasised that the w / b ratio was maintained constant. Thus, the workability was reduced significantly with an increase in the amount of red mud added. The properties of concrete should be examined further by varying the w / b ratio and using additives.

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