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Technical Note

A New Approach to Mix Design of Green Concrete Using Slag

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A new method for designing the mix proportions of green concrete using slag has been proposed. The approach includes three different mixes: the first mix (1 : 2.62 : 4.87) used 275 kg/m^3 of cement, the second mix (1: 2.38: 4.42) used 300 kg/m^3 of cement, and the third mix (1 : 1.99 : 3.7) used 350 kg/m^3 of cement. The green concrete mixes for these groups were produced with 35%, 40%, and 45% slag powder as partial replacement for the weight of cement. The results showed that the compressive strength of green concrete at 28 days for 35% substitution was approximately similar to that of the reference concrete. However, for 40% and 45% replacements, the compressive strength was reduced by 9.4% and 20.4%, respectively. Additionally, the CO_2 emission and costs associated with producing 1 m^3 of reference and green concrete were considered in this study. The incorporation of 35%, 40%, and 45% slag powder as a cement substitution reduced CO_2 emissions by 24.7%, 28.7%, and 33.1%, and production costs by 16%, 16.8%, and 17.4%, respectively, compared to reference concrete. The suggested mix design approach for green concrete was developed using seven equations for preparing the mix proportion. Most of the equations achieved an R^2 of about 0.9, except for the equation determining binder content, which had an R^2 of about 0.8. The suggested approach depends on the compressive strength, slump, and superplasticizer dosage. The results show the ability of the proposed approach to achieve compressive strength higher than the design compressive strength.

Keywords: green concrete; slag; cement; mix design; CO_2 emission; cost.

Abbreviations

A/B – aggregate-to-binder ratio,
ASTM – American Society for Testing and Materials,
B – binder,

CO_2	–	carbon dioxide,
COM	–	compressive strength,
IQD	–	Iraqi dinars,
QS	–	Iraq specifications,
R^2	–	coefficient of determination,
SL	–	slump test,
SP	–	superplasticizer percentage,
SR	–	slag powder percentage,
W	–	water,
W/B	–	water-to-binder ratio.

1. Introduction

The construction industry's rapid growth and activity have raised concerns due to its unsustainable practices, which rely on nonrenewable resources and result in significant greenhouse gas emissions and waste [1, 2]. These practices pose significant threats to the environment and human civilization, contributing to global warming, now a critical sustainability concern [3]. To address these challenges, the construction industry must adopt alternative approaches that can reduce its environmental impact.

One promising solution is green concrete, which incorporates waste materials as replacements for cement, thereby reducing the environmental impact of its production [4, 5]. Green concrete is designed not only to be eco-friendly but also to deliver high performance and durability. In other words, it should contribute to the environment and improve sustainability across environmental, social, and economic dimensions [6–8].

Cement, a key component in traditional concrete, is a major contributor to carbon dioxide emissions during its production [9]. The use of in-situ cement additives could attenuate this impact. Cement is also the most energy-consuming and costly concrete product [10, 11]. With the increasing demand for construction, global cement production is predicted to reach 4.83 billion tons by 2030. This increase in cement production necessitates an proportional increase in resources, including natural stones utilized as aggregates [12]. However, by partially substituting cement with waste materials rich in pozzolanic properties, the cost of concrete can be reduced, lessening its environmental impact [13]. Various experiments and innovations have focused on finding alternative binder materials derived from agricultural and industrial sources, processed either naturally or artificially [14].

Cost-efficient and alternative building methods play a crucial role in reducing CO_2 emissions. Employing low-energy alternative materials such as wood ash, silica fume, rice husk ash, fly ash, slag, and other waste products in concrete can decrease its environmental impacts [15–17]. For instance, slag, a by-product of pig iron production, can be utilized in green concrete, addressing waste disposal issues while benefiting both the cement and steel industries [18, 19].

In addition to using alternative materials, the mix design process plays a vital role for achieving high-performance green concrete. The mix design process aims to determine the optimal combination of materials to meet the target compressive strength-a critical property of concrete that defines its class and ensures safety and durability [20].

By focusing on the development of green concrete, the construction industry can significantly contribute to reducing its environmental footprint and moving towards a more sustainable and eco-friendly future. Green concrete offers a viable and effective solution to the challenges posed by traditional concrete production, promoting a more environmentally conscious approach to construction practices.

The primary objective of this research is to propose a mix design approach for green concrete and to investigate the properties of green structural concrete with varying proportions of cement replaced by slag through rigorous testing. Additionally, the aim is to reduce carbon dioxide emissions and energy/fuel consumption in cement manufacturing by utilizing cementitious materials as alternatives to cement, while also assessing the mechanical properties and environmental impact of the resulting green concrete.

To achieve this objective, the study involved conducting destructive laboratory tests on various concrete mixtures, creating a comprehensive database of concrete recipes. The test results were then utilized as input for the selected ideal mix design framework, which involved mathematical formulas applicable to real-world scenarios. This mix design approach can serve as an initial tool for evaluating the green concrete's performance and potential in its current state.

This research primarily focused on assessing the compressive strength of different concrete mixes, with emphasis on the role of superplasticizers and other additives in achieving the desired strength properties. Superplasticizers are commonly used to improve the workability and flow of concrete without increasing water content, which can help optimize the compressive strength of green concrete mixes.

By exploring and understanding the mechanical properties and environmental impact of green concrete with various cement replacement ratios, the research aims to contribute to the development of more sustainable and eco-friendly construction practices. By reducing carbon dioxide emissions and energy consumption in cement production along with promoting the use of alternative cementitious materials, this study seeks to address the environmental challenges posed by traditional concrete manufacturing. Ultimately, the proposed mix design approach, along with the insights gained from this research, can pave the way for the wider adoption of green concrete in the construction industry.

2. Materials

2.1. Cement

Various green concrete mixes were produced using locally available cement, specifically the ordinary Portland cement (Type I) from the Badosh cement factory in Iraq. The chemical composition and physical properties of the cement are presented in Tables 1 and 2. The test results demonstrate that the cement meets the requirements set forth in ASTM C150-17 [21] and also complies with Iraqi Specifications No. 5-1984 [22]. The testing for both the chemical composition and physical properties of the cement was conducted by the Badosh cement factory laboratories.

Table 1. Chemical compositions of Badosh cement used.

Chemical elements	Elements in cement [%]	Limitations of the ASTM C150-17 [%]	Limitations of the QS No.5-1984 [%]
SiO_2	20.89	–	–
Al_2O_3	5.87	–	–
Fe_2O_3	2.8	–	–
CaO	62.36	–	–
MgO	4.21	≤ 6	≤ 5
SO_3	2.24	≤ 3.5 if $C_3A \geq 8$	≤ 2.8 if $C_3A \geq 5$
Loss of ignition	1.4	≤ 3	≤ 4.0
Insoluble residue	0.89	≤ 1.5	≤ 1.5
Free CaO	1.62	–	–
L.S.F	0.903	–	(0.66–1.02)
C_3S	45.2	–	–
C_2S	25.87	–	–
C_3A	10.82	–	–
C_4AF	8.51	–	–

Table 2. Physical properties of Badosh cement used.

Tests	Results	Limitations of the ASTM C150-17	Limitations of the QS No.5-1984
Start setting time (Vicat test)	145 min	Min. 45 min	Min. 45 min
Finish setting time (Vicat test)	189 min	Max. 375 min	Max. 600 min
Fineness (Blaine test)	306.5 m^2/kg	Min. 260 m^2/kg	Min. 230 m^2/kg
50 mm cubic mortar compressive strength			
3 days	16.71 MPa	Min. 12 MPa	Min. 15 MPa
7 days	25.96 MPa	Min. 19 MPa	Min. 23 MPa
28 days	33.88 MPa	–	–

2.2. *Sand*

The local natural fine aggregate used in the study was sourced from the Kanhash region in Mosul. The sand collected from this source has the following properties, in accordance with ASTM C128-15 [23]: specific gravity of 2.66, water absorption of 1% and bulk density of 1735 kg/m^3. Furthermore, the sand's grading standards meet the requirements of ASTM C33-16 [24]. The grading details are summarized in Table 3.

TABLE 3. Grading of sand (fine aggregate).

No.	Sieve No. (mm)	Passing [%]	Limitations of the ASTM C33-16 [%]
1	3/8-in. (9.5)	100	100
2	No. 4 (4.75)	95.58	95–100
3	No. 8 (2.36)	81.49	80–100
4	No. 16 (1.18)	67.21	50–85
5	No. 30 (0.6)	34.46	25–60
6	No. 50 (0.3)	18.31	5–30
7	No. 100 (0.15)	5.23	0–10
8	No. 200 (0.075)	1.21	0–3

2.3. *Gravel*

The study utilized natural rounded coarse aggregate with a maximum aggregate size of 12.5 mm. The coarse aggregate was obtained from the local Mosul River (Tigris). The properties of the coarse aggregate, determined by ASTM C127-15[25], are as follows: specific gravity of 2.66, water absorption of 0.5%, and bulk density of 1670 kg/m^3. The grading of the gravel used adheres to the specifications outlined in ASTM C33-16 [24]. The grading details are summarized in Table 4.

TABLE 4. Grading of gravel (coarse aggregate).

No.	Sieve No. (mm)	Passing [%]	Limitations of the ASTM C33-16 [%]
1	3/4-in. (19)	100	100
2	1/2-in. (12.5)	93	90–100
3	3/8-in. (9.5)	59	40–70
4	No. 4 (4.75)	0.9	0–15
5	No. 8 (2.36)	0	0–5

2.4. *Slag powder*

In this research, slag, an industrial byproduct resulting from high-temperature iron smelting, was utilized to develop green structural concrete. The slag used in the study was collected from a nearby steel factory in Zakho, Iraq. The chemical and physical properties of the slag are detailed in Tables 5 and 6, respectively. The evaluation of these properties was carried out following the standards specified in ASTM C989-16 [26]. Additionally, the strength activity index of the slag powder was determined using ASTM C311-16 [27]. The testing of the chemical composition properties of the slag was conducted by the Iron and Steel Factory Laboratory in Zakho.

Table 5. Chemical compositions for slag powder used.

Chemical elements	Elements in slag [%]	Limitations of the ASTM C989-16 [%]
SiO_2	35.8	–
Al_2O_3	13.7	–
Fe_2O_3	1.3	–
MnO_2	0.58	–
CaO	41.7	–
SO_3	0.092	–
K_2O	1.35	–
Na_2O	0.33	–
MgO	1.493	–
TiO_2	0.452	–
P_2O_5	0.06	–
Loss of ignition	0.68	–
Sulfide sulfur (S)	0.143	$\leq$ 2.5

Table 6. Physical and mechanical properties of slag powder used.

Tests	Results	Limitations of the ASTM C989-16
Type	Powder	–
Color	Dark gray – black	–
Specific gravity	2.88	–
Bulk density [kg/m^3]	1478	–
Fineness (Blaine test) [m^2/kg]	365.4	
Slag activity index in 28 days [%]	76.217	$\geq$ 75 for slag grade 80

2.5. Superplasticizer

In this study, a high-range concrete superplasticizer admixture known as Floc-rete SP-42 was employed. This admixture is produced by Don Construction Products (DCP) and is designed to be a high-performance fluid concrete admixture comprising selected polymers. Its primary purpose is to improve the effectiveness of the concrete's water content. By significantly reducing the water content in the concrete mix, Floc-rete SP-42 enhances both workability and ultimate strength of the concrete. Depending on the dosage used, Floc-rete SP-42 complies with ASTM C494-17 [28], specifications for type B, D, and G superplasticizers. The technical characteristics of Floc-rete SP-42, as per the datasheet [29], are summarized in Table 7.

Table 7. Technical properties of the Floc-rete SP-42 used.

Tests	Results
State of the materials	Liquid
Color	Brown-black
Specific gravity	1.19–1.22
Chloride content	Nil
Air entrainment	Less than 2%
Structure	Sulfonated Naphthalene

2.6. Water

In the mixing process, tap water was utilized. It is essential that the water used in both the mixing and curing processes is free from organic matter, oils, and any other potentially harmful substances. This ensures the quality and integrity of the concrete being produced. During the curing process, the samples were exposed to the same water conditions as those used in the mixing process, maintaining the requirement for clean and uncontaminated water to achieve accurate and reliable results.

3. Experimental procedure

In this study, all concrete mixes followed the specifications outlined in ASTM C192-16 [30] for the processes of mixing, casting, and curing. This ASTM standard sets forth uniform guidelines for the preparation of materials, concrete mixing procedures, as well as the fabrication and curing of concrete test specimens in laboratory conditions. Adhering to these standardized procedures ensures consistency and reliability in the experimental process, allowing for meaningful comparisons and analysis of the concrete's properties and performance.

3.1. Mix proportions

In the initial stage of the experimental work, reference concrete mixes with medium strength (structural concrete) were designed for target compressive strengths of 20 MPa, 25 MPa, and 30 MPa. The British Department of Environment's Design Method (DOE Method) was used for this purpose, which is presently considered the standard British method (BS method) for concrete mix design [31]. The DOE Method conforms to the specifications provided in BS EN 206-1, along with its complementary standards such as BS 8500-1 [32], BS 8500-2 [33] and BS 8110-1 [34].

These British standards and European norms play a crucial role in guiding the concrete mix design process, ensuring that the resulting concrete meets the required strength and performance criteria for structural applications.

In this research, three groups of concrete mixes were used, with each mix described by the ratio of cement, sand, and gravel used. The details for each group are as follows.

3.1.1. Group 1 (Symbol: R). Specifications:

- Mix proportion: 1 : 2.62 : 4.87;
- Cementitious material: 275 kg (constant for all mixes in this group);
- Water/cement ratio: the same for all mixes in this group;
- Superplasticizer: different ratios were used to achieve the required slump for each mix;
- Reference concrete mixes (R1, R2, R3, and R4): contained 275 kg of ordinary Portland cement only (100% cement + 0% slag) with varying slumps achieved through different superplasticizer ratios;
- Green concrete mixes (R5, R6, R7, and R8): contained 178.75 kg of ordinary Portland cement and 96.25 kg of slag powder (65% cement + 35% slag) with varying slumps achieved through different superplasticizer ratios.

3.1.2. Group 2 (Symbol: S). Specifications:

- Mix proportion: 1 : 2.38 : 4.42;
- Cementitious material: 300 kg (constant for all mixes in this group);
- Water/cement ratio: the same for all mixes in this group;
- Superplasticizer: different ratios were used to achieve the required slump for each mix;
- Reference concrete mixes (S1, S2, S3, and S4): contained 300 kg of ordinary Portland cement only (100% cement + 0% slag) with varying slumps achieved through different superplasticizer ratios.
- Green concrete mixes (S5, S6, S7, and S8): contained 180 kg of ordinary Portland cement and 120 kg of slag powder (60% cement + 40% slag) with varying slumps achieved through different superplasticizer ratios.

3.1.3. Group 3 (Symbol: T). Specifications:

- Mixproportion: 1 : 1.99 : 3.7;
- Cementitious material: 350 kg (constant for all mixes in this group);

- Water/cement ratio: the same for all mixes in this group;
- Superplasticizer: different ratios were used to achieve the required slump for each mix.
- Reference concrete mixes (T1, T2, T3, and T4): contained 350 kg of ordinary Portland cement only (100% cement + 0% slag) with varying slumps achieved through different superplasticizer ratios;
- Green concrete mixes (T5, T6, T7, and T8): contained 192.5 kg of ordinary Portland cement and 157.5 kg of slag powder (55% cement + 45% slag) with varying slumps achieved through different superplasticizer ratios.

The researchers maintained constant weights of sand and gravel for all mixes within each group. The water/cement ratio was also consistent within each group. The quantity of superplasticizer, water, and slag powder replacement was determined based on the weight of cement used in each mix. Specific details of the mixes and their corresponding properties can be found in Table 8 for group 1, Table 9 for group 2, and Table 10 for group 3.

Table 8. Mix proportion for group 1.

Mixes	Cement [kg/m^3]	Slag [kg/m^3]	Sand [kg/m^3]	Gravel [kg/m^3]	W/B [%]	Water [kg/m^3]	SP [%]	SP [kg/m^3]
R1	275	0	721	1339	0.44	121	0	0
R2	275	0	721	1339	0.44	121	0.35	0.963
R3	275	0	721	1339	0.44	121	0.55	1.513
R4	275	0	721	1339	0.44	121	0.75	2.063
R5	178.75	96.25	721	1339	0.44	121	0.95	2.613
R6	178.75	96.25	721	1339	0.44	121	1.05	2.888
R7	178.75	96.25	721	1339	0.44	121	1.15	3.163
R8	178.75	96.25	721	1339	0.44	121	1.25	3.438

Table 9. Mix proportion for group 2.

Mixes	Cement [kg/m^3]	Slag [kg/m^3]	Sand [kg/m^3]	Gravel [kg/m^3]	W/B [%]	Water [kg/m^3]	SP [%]	SP [kg/m^3]
S1	300	0	714	1326	0.42	126	0	0
S2	300	0	714	1326	0.42	126	0.31	0.93
S3	300	0	714	1326	0.42	126	0.51	1.53
S4	300	0	714	1326	0.42	126	0.72	2.16
S5	180	120	714	1326	0.42	126	0.98	2.94
S6	180	120	714	1326	0.42	126	1.17	3.51
S7	180	120	714	1326	0.42	126	1.37	4.11
S8	180	120	714	1326	0.42	126	1.56	4.68

TABLE 10. Mix proportion for group 3.

Mixes	Cement [kg/m^3]	Slag [kg/m^3]	Sand [kg/m^3]	Gravel [kg/m^3]	W/B [%]	Water [kg/m^3]	SP [%]	SP [kg/m^3]
T1	350	0	696.5	1295.5	0.366	128	0	0
T2	350	0	696.5	1295.5	0.366	128	0.29	1.015
T3	350	0	696.5	1295.5	0.366	128	0.48	1.68
T4	350	0	696.5	1295.5	0.366	128	0.68	2.38
T5	192.5	157.5	696.5	1295.5	0.366	128	1.4	4.9
T6	192.5	157.5	696.5	1295.5	0.366	128	1.6	5.6
T7	192.5	157.5	696.5	1295.5	0.366	128	1.8	6.3
T8	192.5	157.5	696.5	1295.5	0.366	128	2	7

3.2. Mix procedure

The mix procedure for both the reference concrete and green concrete in this research involved the following steps:

- *Materials selection:* The appropriate materials, including cement, sand, gravel, superplasticizer, and slag powder, were chosen based on the desired mix proportions for each group.
- *Mold preparation:* Molds required for casting the concrete specimens were prepared in the workshop. The casting yard was set up to accommodate all the molds needed for the concrete pour.
- *Fresh concrete testing equipment:* Equipment for testing the fresh concrete properties, such as slump testing equipment, was made available to monitor the workability of the concrete mixes.
- *Drum mixer:* A drum mixer (electric concrete mixer) with a drum capacity of 180 liters was used for mixing the concrete. Figure 1 depicts the concrete mixer used.
- *Material weighing:* Accurate balances were used to measure the materials. Two balances were employed for this purpose: one with a capacity of 40 kg and an accuracy of up to 2 grams, used for weighing cementitious materials, sand, and gravel; the other with a capacity of 10 kg and an accuracy of up to 1 gram, used for weighing superplasticizer and water.
- *Mixing methodology:* The mixing process involved the following steps:
  (1) wetting the inner surfaces of the concrete mixer's drum,
  (2) adding gravel into the mixer, followed by sand and cementitious materials. These materials were combined in a dry state in the drum mixer, and the dry mixing typically took about 3 minutes,
  (3) two-thirds of the mixing water was added, and the mix was mixed for two minute,

(4) the remaining water and superplasticizer were added to the mixer, and mixing continued until the mixture appeared homogeneous.

- *Casting and compaction:* The prepared molds were oiled, and the fresh concrete was poured into the molds. For each test, two layers of cubes with dimensions of $100 \times 100 \times 100$ mm were cast. Each layer was compacted using a suitable tamping rod with 25 strokes. After compaction, the top of the specimens was smoothed using a trowel.
- *Slag powder mixing:* The required quantity of slag powder was mixed with cement. This mixing process lasted for 20 minutes to ensure thorough dispersion of the slag powder particles between the cement particles.

By following this mix procedure, the researchers were able to produce and test both the reference and green concrete mixes, each with different proportions and slumps, as described in the study.

a) b)

Fig. 1. a) Electric concrete mixer (drum volume 180 dm^3); b) green concrete mix.

4. Results and discussions

4.1. Workability

Slump testing was used to determine workability of the concrete. Table 11 shows the slump values for both the reference concrete and green concrete mixes containing partial cement replacement with slag powder for groups 1, 2, and 3. The British DOE Method for mix design of concrete provides slump test ranges of 0–10 mm, 10–30 mm, 30–60 mm, and 60–180 mm, which were used for comparison with the resulting green concrete.

For mixes in group 1, the results showed that the green concrete mix R5 has the same slump range compared with a slump of reference concrete mix R1; the slump range for two mixes R1 and R5 falls in the range of 0–10 mm. The green

TABLE 11. Slump test results for groups 1, 2, and 3.

Mixes	Cement [kg/m^3]	Slag [kg/m^3]	Water [kg/m^3]	SP [kg/m^3]	Slump [mm]
Group 1 (35% replacement)					
R1	275	0	121	0	6
R2	275	0	121	0.963	17
R3	275	0	121	1.513	50
R4	275	0	121	2.063	112
R5	178.75	96.25	121	2.613	5
R6	178.75	96.25	121	2.888	20
R7	178.75	96.25	121	3.163	49
R8	178.75	96.25	121	3.438	116
Group 2 (40% replacement)					
S1	300	0	126	0	5
S2	300	0	126	0.93	13
S3	300	0	126	1.53	36
S4	300	0	126	2.16	117
S5	180	120	126	2.94	6
S6	180	120	126	3.51	16
S7	180	120	126	4.11	41
S8	180	120	126	4.68	120
Group 3 (45% replacement)					
T1	350	0	128	0	3
T2	350	0	128	1.015	18
T3	350	0	128	1.68	42
T4	350	0	128	2.38	110
T5	192.5	157.5	128	4.9	5
T6	192.5	157.5	128	5.6	21
T7	192.5	157.5	128	6.3	48
T8	192.5	157.5	128	7	105

concrete mix R6 has the same slump range compared with a slump of reference concrete mix R2; the slump range for both mixes, R2 and R6, is between 10–30 mm. The green concrete mix R7 has the same slump range compared with a slump of reference concrete mix R3; the slump range for the two mixes, R3 and R7, is between 30–60 mm. The green concrete mix R8 has the same slump range compared with a slump of reference concrete mix R4; the slump range for the R4 and R8 mixes is between 60–180 mm.

For mixes in group 2, the results showed that the green concrete mix S5 has the same slump range compared with a slump of reference concrete mix S1; the slump range for two mixes, S1 and S5, is between 0–10 mm. The green concrete mix S6 has the same slump range as a slump of reference concrete mix S2; the slump range for the S2 and S6 mixes fall in the 10–30 mm range. The green concrete mix S7 had the same slump range as a slump of reference concrete mix S3; the slump range for the S3 and S7 mixes is between 30–60 mm. The green concrete mix S8 has the same slump range compared with a slump of reference concrete mix S4; the slump range for the S4 and S8 mixes is between 60–180 mm.

For mixes in group 3, the results showed that the green concrete mix T5 has the same slump range as the reference concrete mix T1; the slump range for the two mixes, T1 and T5, is between 0–10 mm. The green concrete mix T6 has the same slump range as a slump of reference concrete mix T2; the slump range for the two mixes, T2 and T6, is between 10–30 mm. The green concrete mix T7 has the same slump range compared with a slump of reference concrete mix T3; the slump range for the two mixes, T3 and T7, is between 30–60 mm. The green concrete mix T8 has the same slump range compared with a slump of reference concrete mix T4; the slump range for the T4 and S8 mixes is between 60–180 mm.

In general, the inclusion of slag powder as a partial replacement for cement decreased the workability of the fresh concrete. This reduction in workability is attributed to the sharp edges and rough surface texture of the slag powder particles, which decrease the workability and may increase the water requirements of the concrete mix [35, 36].

To achieve workability comparable to the reference concrete mixes, the green concrete mixes with slag powder replacement (at 35%, 40%, and 45%) required additional water. Therefore, a superplasticizer (Flo-Crete sp42) was added to all mixes in different proportions, based on the percentage of the replaced cement, to improve the slump and workability [37]. Consequently, the mixes in group 3 required more superplasticizer compared to those in groups 1 and 2 to achieve the desired slump [38].

4.2. Compressive strength

Table 12 presents the compressive strength of both reference concrete and green concrete mixes containing partial cement replacement with slag powder at 7 and 28 days for groups 1, 2, and 3.

The results for group1 mixes showed that the compressive strength at 7 and 28 days for mix R5 reduced by approximately 27.3% and increased by about 1.6%, respectively, compared to mix R1. For mix R6, the compressive strength reduced by around 28.3% at 7 days and about 5.4% at 28 days, compared to mix R2. Mix R7 exhibited a reduction of about 23.7% at 7 days and an increase

TABLE 12. Compressive strength results for groups 1, 2 and 3.

Mixes	Cement [kg/m^3]	Slag [kg/m^3]	Water [kg/m^3]	SP [kg/m^3]	Average compressive strength [MPa]	
					7 days	28 days
Group 1 (35% replacement)						
R1	275	0	121	0	22.84	25.21
R2	275	0	121	0.963	23.6	25.86
R3	275	0	121	1.513	22.21	24.79
R4	275	0	121	2.063	24.85	26.06
R5	178.75	96.25	121	2.613	16.61	25.63
R6	178.75	96.25	121	2.888	16.92	24.47
R7	178.75	96.25	121	3.163	16.95	26.63
R8	178.75	96.25	121	3.438	16.22	24.01
Group 2 (40% replacement)						
S1	300	0	126	0	26.54	33.18
S2	300	0	126	0.93	28.03	34.69
S3	300	0	126	1.53	28.23	33.2
S4	300	0	126	2.16	28.14	33.76
S5	180	120	126	2.94	18.27	30.47
S6	180	120	126	3.51	18.31	32.18
S7	180	120	126	4.11	17.69	30.07
S8	180	120	126	4.68	17.90	29.48
Group 3 (45% replacement)						
T1	350	0	128	0	35.95	39.03
T2	350	0	128	1.015	36.10	43.08
T3	350	0	128	1.68	34.88	40.33
T4	350	0	128	2.38	34.66	42.35
T5	192.5	157.5	128	4.9	21.37	30.33
T6	192.5	157.5	128	5.6	20.90	33.90
T7	192.5	157.5	128	6.3	20.18	34.59
T8	192.5	157.5	128	7	20.17	32.29

of about 6.9% at 28 days, compared to mix R3. As for mix R8, the compressive strength reduced by about 34.7% at 7 days and 7.8% at 28 days, compared to mix R4.

Although there are differences in the compressive strength values between green concrete and reference concrete at 28 days, the compressive strength for all green concrete mixes in group 1 remained within the target compressive strength of C20 at 28 days.

For group 2, the results indicated that the compressive strength at 7 and 28 days for mix S5 reduced by approximately 31.1% and about 8.2%, respectively, compared to mix S1. Mix S6 exhibited a reduction of about 34.6% and about 7.2%, respectively, compared to mix S2. For mix S7, the compressive strength reduced by about 37.3% and about 9.4%, respectively, compared to mix S3. As for mix S8, the compressive strength was reduced by around 36.4% and about 12.7%, respectively, compared to mix S4.

Similarly, the compressive strength for all green concrete mixes in group 2 remained within the target compressive strength of C25 at 28 days.

Next, in group 3, the results indicated that the compressive strength at 7 and 28 days for mix T5 reduced by about 40.6% and about 22.3%, respectively, compared with mix T1. Mix T6 exhibited a reduction of about 42.1% and about 21.3%, respectively, compared with mix T2. For mix T7, the compressive strength reduced by about 42.1% and about 14.2%, respectively, compared with mix T3. As for mix T8, the compressive strength was reduced by approximately 41.8% and about 23.7%, respectively, compared with mix T4.

Just like in the previous groups, the compressive strength for all green concrete mixes in group 3 at 28 days remained within the target compressive strength C30.

The overall findings showed that when cement was substituted with slag powder by 35% for mixes R5–R8, the compressive strength provided results almost similar to the reference concrete mixes R1–R4. However, with a replacement of 40% and 45% for mixes S5–S8 and T5–T8, the compressive strength reduced by about 9.4% and 20.4%, respectively, compared to the reference concrete mixes S1–S4 and T1–T4, as shown in Fig. 2. These results are consistent with findings of Wang's research [39].

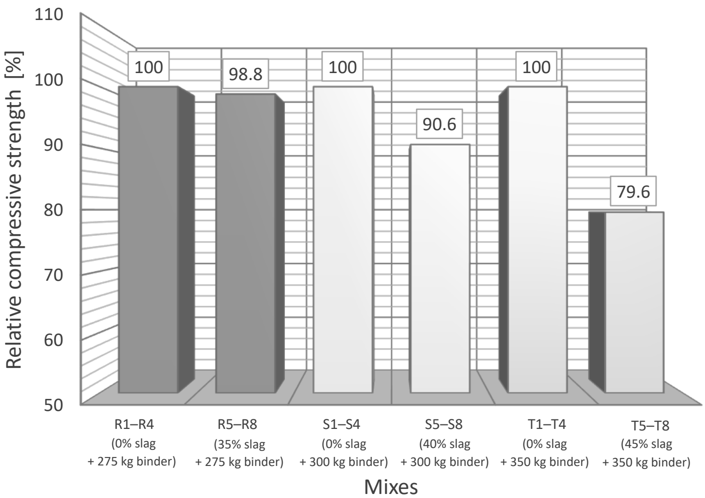

Fig. 2. Relative compressive strength at 28 days.

Furthermore, the results indicated that green concrete mixes containing slag powder as a replacement for cement initially exhibit lower early-age strength than reference concrete. However, the strength of the green concrete mix improves with age and provides equivalent compressive strength compared with the reference concrete. For all the green concrete mixes in the three groups, the compressive strength of green concrete was lower than that of reference concrete at 7 days. However, the compressive strength of green concrete developed at 28 days [40, 41].

The compressive strength of green concrete in group 3 was lower than the compressive strength of groups 1 and 2 compared with the reference concrete for each respective group. This is because the compressive strength decreased with an increase in the slag powder replacement percentage [42, 43].

In general, the inclusion of slag powder reduced the compressive strength of green concrete at early ages. This decrease was more pronounced with an increased slag powder content in the green concrete mix. This is because the presence of slag powder slows down the hydration process, requiring a longer curing period. As a result, the strength development of green concrete mixes is slower than that of reference concrete mixes when the heat of hydration is reduced [44, 45].

4.3. Effect of slag powder on reducing the CO_2 emissions

This part of the research aims to determine the quantities of carbon dioxide (CO_2) probable for the mixes containing cement as the sole binder and those containing slag as a partial replacement of cement.

A commonly used CO_2 emission calculation method is the carbon emission factor method. This method estimates CO_2 emission by multiplying the quantity of material by its respective CO_2 emission factor. The advantage of this method is that the calculation is convenient, direct and highly reliable. However, its disadvantage is the considerable diversity, which requires detailed active data [46, 47].

The amount of CO_2 emission was calculated for the components of 1 m^3 of concrete, taking into account materials such as cement, fine aggregate (sand), coarse aggregate (gravel), superplasticizer, and slag powder (used as a partial cement replacement). The CO_2 emissions for each component of the reference concrete and green concrete mixes were then summed to determine the total CO_2 emissions for 1 m^3 of concrete.

The values of emission factors used in assessing the environmental impact of the materials in both reference concrete and green concrete can be found in Table 13.

TABLE 13. Description of CO_2 emission factors.

No.	Material	Details	CO_2 emission factor [kg CO_2-eq per kg]
1	Cement [46]	Includes material processing such as quarrying, grinding of raw material, clinker cooling, and grinding after production. As shown in the manufacture with 2000 t/d manufacturing line by dry process procedure	0.92
2	Fine aggregate [48, 49]	Quarrying and fine aggregate refining are modeled as they would occur in Australia.	0.014
3	Coarse aggregate [48, 49]	Quarrying and coarse aggregate refining are modeled as they would occur in Australia.	0.041
4	Superplasticizer [50]	Includes all stages of the manufacturing process, from raw material procurement to chemical additive synthesis, based on European datasets.	0.767
5	Slag powder [50]	Includes slag collection, processing, and refinement, designed after conditions found in the USA.	0.085

The estimated CO_2 emissions from reference concrete and green concrete mixes for groups 1, 2 and 3 are shown in Table 14.

The results in Table 14 indicate that CO_2 emissions are related to the percentages of cement replacement and the different CO_2 emission factors for the constituents of concrete. For mixes in group 1, when utilizing 35% slag powder as a cement replacement, the results showed that the green concrete mixes R5–R8 that average CO_2 emissions that decreased by about 24.7% compared to the reference concrete mixes R1–R4. When using 40% slag powder as a cement replacement in group 2 mixes, the average CO_2 emissions of the green concrete mixes S5–S8 were reduced by roughly 28.7% compared to the reference concrete mixes S1–S4. In group 3, when 45% slag powder is used in place of cement, the results indicated that the green concrete mixes T5–T8, had average CO_2 emissions that were reduced by approximately 33.1% compared to reference concrete mixes T1–T4.

From the results, using slag powder as a partial replacement for cement reduces CO_2 emissions induced by fossil fuel combustion and power consumption in cement production [51, 52]. Therefore, the CO_2 emission factor for cement production is much higher than the emission factor of slag powder treatment [53]. Slag powder is an environmentally favorable modification for concrete production. As a result, it can be inferred that the eco-friendliness of green concrete

TABLE 14. CO_2 emissions estimates for groups 1, 2, and 3.

Mixes	CO_2 for cement [kg/m^3]	CO_2 for slag [kg/m^3]	CO_2 for sand [kg/m^3]	CO_2 for gravel [kg/m^3]	CO_2 for SP [kg/m^3]	Total CO_2 [kg/m^3]	Average total CO_2 [kg/m^3]
Group 1 (35% replacement)							
R1	253	0	10.1	54.9	0	318	318.9
R2	253	0	10.1	54.9	0.74	318.7	
R3	253	0	10.1	54.9	1.16	319.2	
R4	253	0	10.1	54.9	1.58	319.6	
R5	164.45	8.18	10.1	54.9	2	239.6	240
R6	164.45	8.18	10.1	54.9	2.22	239.9	
R7	164.45	8.18	10.1	54.9	2.43	240.1	
R8	164.45	8.18	10.1	54.9	2.64	240.3	
Group 2 (40% replacement)							
S1	276	0	10	54.4	0	340.4	341.3
S2	276	0	10	54.4	0.7	341.1	
S3	276	0	10	54.4	1.2	341.6	
S4	276	0	10	54.4	1.7	342.1	
S5	165.6	10.2	10	54.4	2.3	242.5	243.2
S6	165.6	10.2	10	54.4	2.7	242.9	
S7	165.6	10.2	10	54.4	3.2	243.4	
S8	165.6	10.2	10	54.4	3.6	243.8	
Group 3 (45% replacement)							
T1	322	0	9.75	53.12	0	384.9	385.9
T2	322	0	9.75	53.12	0.78	385.7	
T3	322	0	9.75	53.12	1.29	386.2	
T4	322	0	9.75	53.12	1.83	386.7	
T5	177.1	13.39	9.75	53.12	3.76	257.1	258
T6	177.1	13.39	9.75	53.12	4.3	257.7	
T7	177.1	13.39	9.75	53.12	4.8	258.2	
T8	177.1	13.39	9.75	53.12	5.4	258.8	

mixes improves to varying degrees in proportion to the slag powder replacement amounts [54].

4.4. Effect of slag powder on reducing the cost of concrete

In this section of the research, the focus is on determining the cost of different concrete mixes, specifically comparing mixes using cement solely as a binder with mixes that include slag powder as a partial substitution for cement. The cost assessment involves considering various components that contribute to the overall cost of 1 m^3 of concrete. These components include cement, fine aggregate (sand), coarse aggregate (gravel), superplasticizer, water, and slag powder (when used as a replacement for cement) [55, 56]. To calculate the cost of 1 m^3 of concrete, the research team took into account the current market prices of these materials.

The cost estimation considered the expenses related to the production, extraction from quarries, washing the materials, treatment, and transportation distances to the city center of Mosul [57]. The cost values used for determining the cost of each component of both the reference concrete (mixes with cement only) and green concrete (mixes with slag powder as a partial cement replacement) are presented in Table 15.

TABLE 15. Description of the details of the concrete components cost.

No.	Material	Details	IQD/kg	EUR/kg
1	Cement	Every 1000 kg = 110,000 IQD	110	0.078
2	Slag powder*	Every truck contains 10 m^3 = 250,000 IQD and every 1 m^3 = 1478 kg	16.9	0.012
3	Fine aggregate	Every truck contains 10 m^3 = 170,000 IQD and every 1 m^3 = 1735 kg	9.8	0.0069
4	Coarse aggregate	Every truck contains 10 m^3 = 90,000 IQD and every 1 m^3 = 1670 kg	5.4	0.0038
5	Water	Every truck contains 10,000 dm^3 or kg = 30,000 IQD	3	0.0021
6	Superplasticizer	Every container contains 1000 dm^3 = 1,350,000 IQD and every 1000 dm^3 = 1210 kg	1115.7	0.79

* Based on the provided information, the total cost for preparing slag powder locally is 250,000 IQD (176.62 EUR) per truck. This cost includes the cost of slag powder grinding in crusher factories in Mosul (190,000 IQD) (134.23 EUR), as well as the transportation cost of slag from the iron and steel factory to the crusher factories (30,000 IQD) (21.19 EUR) and from the crusher factories to the project or ready-mix concrete plant (30,000 IQD) (21.19 EUR).

The analysis presented in Table 16 demonstrates the cost comparison between reference concrete mixes (cement binder only) and green concrete mixes with partial cement replacement using slag powder. The costs were estimated after conducting a market survey using locally available materials for producing 1 m^3 of both reference and green concrete.

It should be noted that the cost reductions are related to the percentages of cement replacement with slag powder in each mix group [58]. The findings for each mix group are as follows:

- Group 1: When utilizing 35% slag powder as a cement replacement, the average costs of green concrete mixes (R5–R8) were reduced by approxi-

TABLE 16. Cost analysis for groups 1, 2 and 3.

Mixes	Cost for cement [IQD]	Cost for slag [IQD]	Cost for sand [IQD]	Cost for gravel [IQD]	Cost for water [IQD]	Cost for SP [IQD]	Total cost [IQD]	Average cost [IQD]	Average cost [EUR]
Group 1 (35% replacement)									
R1	30,250	0	7066	7230	363	0	44,909	46,175	32.62
R2	30,250	0	7066	7230	363	1074	45,983		
R3	30,250	0	7066	7230	363	1688	46,597		
R4	30,250	0	7066	7230	363	2301	47,210		
R5	19,663	1627	7066	7230	363	683	36,632	38,766	27.39
R6	19,663	1627	7066	7230	363	3222	39,171		
R7	19,663	1627	7066	7230	363	3528	39,477		
R8	19,663	1627	7066	7230	363	3835	39,784		
Group 2 (40% replacement)									
S1	33,000	0	6997	7160	378	0	47,535	48,824	34.49
S2	33,000	0	6997	7160	378	1037	48,572		
S3	33,000	0	6997	7160	378	1707	49,242		
S4	33,000	0	6997	7160	378	2410	49,945		
S5	19,800	2028	6997	7160	378	3280	39,643	40,614	28.69
S6	19,800	2028	6997	7160	378	3916	40,279		
S7	19,800	2028	6997	7160	378	4585	40,948		
S8	19,800	2028	6997	7160	378	5221	41,584		
Group 3 (45% replacement)									
T1	38,500	0	6826	6996	384	0	52,706	54,121	38.23
T2	38,500	0	6826	6996	384	1132	53,838		
T3	38,500	0	6826	6996	384	1874	54,580		
T4	38,500	0	6826	6996	384	2655	55,361		
T5	21,175	2662	6826	6996	384	5467	43,510	44,681	31.57
T6	21,175	2662	6826	6996	384	6248	44,291		
T7	21,175	2662	6826	6996	384	7028	45,071		
T8	21,175	2662	6826	6996	384	7810	45,853		

mately 16% compared to the reference concrete mixes (R1–R4). This reduction in cost amounts to around 7409 IQD (5.23 EUR) per 1 m^3 of concrete.

- Group 2: When using 40% slag powder as a cement replacement, the average costs of green concrete mixes (S5–S8) were reduced by roughly 16.8% compared to the reference concrete mixes (S1–S4). This reduction in cost amounts to around 8210 IQD (5.80 EUR) per 1 m^3 of concrete.

- Group 3: When 45% slag powder is used in place of cement, the results indicate that the average costs of green concrete mixes (T5–T8) were reduced by approximately 17.4% compared to the reference concrete mixes (T1–T4). This reduction in cost amounts to around 9440 IQD (6.67 EUR) per 1 m^3 of concrete.

Based on the findings presented in Table 16, it is evident that using slag powder as a partial replacement for cement in green concrete mixes offers a cost-effective solution for building more sustainable infrastructure. The cost analysis demonstrates a notable reduction in the overall cost of concrete when slag powder is utilized as a cement replacement [59, 60].

Green concrete is generally less expensive than reference concrete because slag powder is available at minimal or no cost, and may only require grinding, treatment, and transportation to the site. Additionally, it does not incur any additional costs during the concrete manufacturing process as money is saved by using less cement [61].

Overall, the combination of cost savings, the availability of slag powder at minimal or no cost, and the environmental advantages of using green concrete makes it an attractive and cost-effective option for building more sustainable infrastructure. It allows construction projects to achieve their objectives with reduced costs while making a positive contribution to environmental conservation.

4.5. Mix design of green concrete by using MS Excel analysis

In the final part of the research, a probabilistic model was developed for the mix design of green concrete incorporating slag powder as a partial replacement for cement. These models were developed based on data analysis conducted in Microsoft Excel, focusing on the various components of green concrete [62]. A regression analysis was performed on several concrete parameters to identify the models that could be used for designing green concrete based on the desired compressive strength.

By utilizing these models, researchers and engineers can optimize the mix proportions of green concrete. This optimization process enables them to find the most suitable combination of materials, including slag powder, to achieve the desired compressive strength while maintaining environmentally friendly and sustainable concrete production.

Overall, the probabilistic models presented a valuable tool for improving the efficiency and effectiveness of green concrete mix design, taking advantage of slag powder as a cement replacement to create durable and eco-friendly concrete structures.

4.5.1. Regression analysis. To analyze the data on green concrete, multiple regression analysis was utilized. Multiple regression analysis is based on the assumption of a linear relationship between the dependent variable and two or more independent variables. All equations considered the independent variables that influence the dependent variable. For instance, the water content affects the compressive strength, superplasticizer percentage, and slump value. As a result, this analysis elucidates the relationship between a single dependent variable and two or more independent variables. The general equation is as follows:

$$Y = C + a_1X_1 + a_2X_2 + ... + a_nX_n, \tag{4.1}$$

where Y – dependent variable, C – constant, $a_1, a_2, ..., a_n$ – slope coefficients, $X_1, X_2, ..., X_n$ – independent variables.

The R-square (R^2) value serves as a crucial indicator for evaluating the accuracy of predictive models, commonly referred to as the coefficient of determination. This metric assesses the goodness-of-fit of linear regression models. The R^2 value represents the proportion of the variance in the dependent variable that is explained by the independent variables, thereby measuring the strength of the relationship between the model and the dependent variable. Its value always falls between 0 and 1.

A higher R^2 value, closer to 1, indicates a more precise fit of the predicted regression equation in describing the relationship between the independent variables (X) and the dependent variable (Y) [63]. In other words, the dependent variable's variation can be better accounted for by the independent variables when R^2 is closer to 1.

The results of the regression analysis conducted on the green concrete mixes can be found in Table 17.

The mix design approach for green concrete mixes involves the use of numerical equations to predict various parameters before preparing the concrete. Each equation represents the relationship between dependent and independent variables based on the experimental data analysis. Below are the numerical equations and their corresponding determination coefficients (R^2):

Step 1. Numerical equation for finding W/B (water-to-binder ratio)

$$\begin{aligned} &\mathrm{W/B} = 0.545 - (0.0005 \times \mathrm{COM}) - (0.105 \times \mathrm{SP}) + (0.00043 \times \mathrm{SL}),\\ &R^2 = 0.905, \end{aligned} \tag{4.2}$$

Step 2. Numerical equation for finding water content

$$\begin{aligned} &\mathrm{W} = 121.05 + (0.567 \times \mathrm{COM}) - (31.762 \times (\mathrm{W/B})) + (0.004 \times \mathrm{SL}),\\ &R^2 = 0.908, \end{aligned} \tag{4.3}$$

TABLE 17. Green concrete mixes.

Mixes	Binder		Water [kg/m^3]	W/B ratio	SP ratio	Sand [kg/m^3]	Gravel [kg/m^3]	A/B ratio	Slump [mm]	Average compressive strength [MPa]
	Cement [kg/m^3]	Slag [kg/m^3]								
Group 1 (35% replacement)										
R5	178.75	96.25	121	0.44	0.95	721	1339	7.5	5	25.63
R6	178.75	96.25	121	0.44	1.05	721	1339	7.5	20	24.47
R7	178.75	96.25	121	0.44	1.15	721	1339	7.5	49	26.63
R8	178.75	96.25	121	0.44	1.25	721	1339	7.5	116	24.01
Group 2 (40% replacement)										
S5	180	120	126	0.42	0.98	714	1326	6.8	6	30.47
S6	180	120	126	0.42	1.17	714	1326	6.8	16	32.18
S7	180	120	126	0.42	1.37	714	1326	6.8	41	30.07
S8	180	120	126	0.42	1.56	714	1326	6.8	120	29.48
Group 3 (45% replacement)										
T5	192.5	157.5	128	0.366	1.4	696.5	1295.5	5.7	5	30.33
T6	192.5	157.5	128	0.366	1.6	696.5	1295.5	5.7	21	33.90
T7	192.5	157.5	128	0.366	1.8	696.5	1295.5	5.7	48	34.59
T8	192.5	157.5	128	0.366	2	696.5	1295.5	5.7	105	32.29

Step 3. Numerical equation for finding binder content

$$\begin{aligned} \mathrm{B} &= -869.98 + (0.223 \times \mathrm{COM}) + (9.374 \times \mathrm{W}), \\ R^2 &= 0.824, \end{aligned} \tag{4.4}$$

Step 4: Numerical equation for finding the ratio of slag powder to replace cement

$$\begin{aligned} \mathrm{SR\%} &= [-1.265 + (0.00017 \times \mathrm{COM}) + (0.0133 \times \mathrm{W})] \times 100, \\ R^2 &= 0.972, \end{aligned} \tag{4.5}$$

Step 5: Numerical equation for finding aggregate/binder ratio A/B

$$\begin{aligned} \mathrm{A/B} &= 14 - (0.0184 \times \mathrm{COM}) - (0.022 \times \mathrm{B}), \\ R^2 &= 0.998, \end{aligned} \tag{4.6}$$

Step 6: Numerical equation for finding sand content

$$\begin{aligned} \mathrm{Sand} &= 592.1 + (0.467 \times \mathrm{COM}) + (15.694 \times (\mathrm{A/B})), \\ R^2 &= 0.993, \end{aligned} \tag{4.7}$$

Step 7: Numerical equation for finding gravel content

$$\text{Gravel} = 1116.2 + (0.724 \times \text{COM}) + (27.4 \times (\text{A/B})), \quad R^2 = 0.994. \tag{4.8}$$

Each equation's determination coefficient (R^2) indicates how well the experimental data fits the proposed equation. A value close to 1 suggests a strong fit, indicating that the equations are reasonably accurate in predicting the respective parameters for green concrete mixes. These equations can be valuable tools in optimizing mix designs and promoting the use of environmentally friendly materials in concrete production.

The variables used in the equations are as follows: W/B – water/binder ratio [%], COM – design compressive strength [MPa], SP – superplasticizer percentage [%], SL – slump value [mm], W – water content [kg], B – binder content [kg], SR% – percentage of slag powder to be replaced from cement [%], sand content [kg], and gravel content [kg].

The mix design approach can be used to design green concrete mixes with partial cement replacement by slag powder, targeting compressive strengths between 20 MPa and 35 MPa. However, it is essential to provide the required values for design compressive strength, superplasticizer percentage, and slump value when using this approach to design a specific mix.

By applying this mix design approach, concrete producers and engineers can optimize their green concrete mixes, making use of sustainable materials and achieving the desired performance characteristics while reducing environmental impact.

4.5.2. Evaluating the MS Excel approach for mix design of green concrete. The reliability of the equations was verified through practical implementation using two examples of green concrete mixes: one with a target compressive strength of C20 and the other with C35. Both mixes were designed to achieve a slump value of 80 mm and a superplasticizer percentage of 1.5%. The mix proportions, calculated using the MS Excel approach, are presented in Table 18.

The results obtained from the first and second mixes are shown in Table 19.

Based on the data presented in Table 19, the first mix(C20) exhibited a slump test result of 75 mm, which was 5 mm lower than the target value of 80 mm. Additionally, the compressive strength at 28 days was 24 MPa, surpassing the expected strength of 20 MPa.

Conversely, the experimental work on the second mix(C35) yielded a slump test result of 85 mm, exceeding the target value of 80 mm by 5 mm. Moreover, the compressive strength at 28 days was 35.62 MPa, which was slightly higher than the expected strength of 35 MPa.

Table 18. Mix proportion for first mix C20 and second mix C35.

Mixes	Binder		Sand [kg/m^3]	Gravel [kg/m^3]	W/B [%]	Water [kg/m^3]	SP [%]	SP [kg/m^3]
	Cement [kg/m^3]	Slag [kg/m^3]						
First mix C20 (32.9% replacement)								
C20	255.8		727	1350	0.412	119.6	1.5	3.84
	171.6	84.2						
Second mix C35 (44.8% replacement)								
C35	341.4		700.3	1301.8	0.404	128.4	1.5	5.12
	188.4	153						

Table 19. Results for the first mix C20 and second mix C35.

Mixes	Average compressive strength [MPa]		Slump [mm]
	7 days	28 days	
C20	17.73	24.73	75
C35	22.60	35.62	85

Overall, the results indicate a satisfactory alignment between the practical and theoretical data for both mixes.

5. Conclusions

The following conclusions are drawn from the testing program used in this study, based on the obtained results:

1) Slag powder reduces the slump of fresh concrete. Additionally, the workability of green concrete decreases with increased slag powder content. To improve the workability of concrete, more water is required. In this case, a superplasticizer is added to enhance the workability of the green concrete.
2) The compressive strength of green concrete with slag powder replacing 35%, 40%, and 45% of cement at 7 days of age decreased by approximately 28.5%, 34.9%, and 41.7%, respectively. However, at 28 days, green concrete with 35% slag powder as a cement substitute provides almost similar compressive strength compared to the reference concrete. For 40% and 45% replacement, the compressive strength reduces by about 9.4% and 20.4%, respectively, compared to the reference concrete for each replacement percentage.
3) Concrete production emits lower CO_2 when slag powder is utilized as a partial substitution for cement. Additionally, concrete produced with slag

powder is environmentally friendly. Green concrete mixes exhibit varying degrees of eco-friendliness depending on the amount of slag powder used. When the percentage of replacement was 35% with a binder content of 275 kg/m^3, 40% with a binder content of 300 kg/m^3, and 45% with a binder content of 350 kg/m^3, the CO_2 emissions were reduced by 24.7%, 28.7%, and 33.1%, respectively.

4) Slag raw material is typically available for free and requires only grinding, treatment and transportation to the location. As a result, green concrete made with slag powder as a partial substitution for cement is less expensive than reference concrete, making it a cost-effective option to develop a more sustainable infrastructure. When the percentage of replacement is 35% with a binder content of 275 kg/m^3, 40% with a binder content of 300 kg/m^3, and 45% with a binder content of 350 kg/m^3, the cost is reduced by about 16%, 16.8%, and 17.4%, respectively.
5) At 28 days, the practical, compressive strength obtained from the suggested mix design approach for green concrete, using slag powder as a substitute for cement, increased by approximately 19.1% and 1.7% for replacement percentages of 32.93% and 44.8%, respectively, compared to the target compressive strength used during the mix design.
6) The new mix design approach of green concrete can be used as a theoretical method for designing green concrete mixes with a suitable range of compatibility between the theoretical values and practical values of mix details and their compressive strengths. Therefore, this approach broadens the scope of green concrete research and could be used to develop customized models for various grades of concrete.

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