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# Concrete matrix based on marble powder, waste glass sludge, and crumb rubber: pathways towards sustainable concrete

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This research aims to develop a sustainable concrete matrix using industrial waste materials, including marble powder, waste glass sludge (WGS), and crumb rubber from tire waste. The mechanical properties of the newly designed concrete mix, such as compressive strength, split tensile strength, and flexural strength, were evaluated. The results showed improvements in compressive strength by 5%, split tensile strength by 4%, and flexural strength by 5%. Besides, a statistical two-way analysis of variance (ANOVA) with a threshold of less than 0.001 was used, and the residual error was found to be low (4.09), both in terms of lack of fit and pure error. This research proposes a new model to assess the sustainable performance of the newly developed concrete matrix. Data was collected from 21 academic professors and structural engineers, and hypotheses were tested using partial least squares structural equation modelling. The Design Expert software was deployed to check its hypothesis, and the Smart PLS software was deployed to measure data validation. The findings demonstrate that a sustainable concrete matrix positively influences sustainable performance. The proposed model offers valuable insights for decision-makers and engineering managers, highlighting the benefits of adopting sustainable materials to enhance overall sustainability performance. Incorporating marble powder, waste glass sludge, and crumb rubber was beneficial in terms of mechanical strengths and microstructure. Overall, this research contributes to the goal of reducing CO<sub>2</sub> emissions in the cement industry and provides practical recommendations for incorporating sustainable materials in construction practices.

## KEYWORDS

sustainable concrete, marble powder, waste glass sludge, crumb rubber, rsm, structural model

## 1 Introduction

The cement industry significantly contributes to 8% of global carbon dioxide (CO<sub>2</sub>) emissions. The construction industry is a major contributor to global energy consumption, and a key part of carbon emissions is attributed to it. The production of one ton of concrete and one ton of cement generates 0.15 and 1 ton of greenhouse gas emissions, respectively. Given the global annual output of 25 billion tons of concrete, these figures have a significant environmental impact. One way to reduce this impact is through green concrete, which incorporates waste, renewable, or supplementary cementitious materials (SCMs) instead of ordinary Portland cement (OPC) or aggregates. SCMs are finely ground pozzolanic materials

that can partially or fully replace OPC in concrete mixtures, improving their fresh and hardened properties (Xiang et al., 2019; Yang et al., 2023; Thomas and Gupta, 2016).

Researchers are investigating various sustainable construction materials to reduce the environmental impact of building and construction projects (Ali et al., 2022; Akbar et al., 2023a; Yang et al., 2023). These sustainable construction materials have been found to perform similarly to traditional cement-based structures (Wang et al., 2019; Chang et al., 2020; Abdelmelek and Lubloy, 2021; Cao et al., 2022; Junaid et al., 2022). Mechanical properties and durability have been extensively studied to ensure the reliability of supplementary cementitious materials (Amin et al., 2020; Ansari and Chang, 2020; Alaloul et al., 2021). Studies have found that replacing a portion of cement with supplementary materials like silica fume (SF) and fly ash (FA) can improve the properties of porous concrete. Up to 5% cement replacement with SF has increased compaction ease, strength, and durability in harsh environments. Combining SF with PVC waste powder as a replacement for ordinary Portland cement (OPC) can also produce concrete with suitable mechanical properties for structural use and be economically and environmentally friendly. Overall, using pozzolanic materials like SF and FA as alternatives to OPC has positively impacted strength and durability in various types of concrete, including geopolymer and self-compacting concrete (Adil et al., 2020; Akbar et al., 2023b; Cao et al., 2023). Similarly, (Umar et al., 2022; Paruthi et al., 2023), concluded that The optimal coal bottom ash dosage for normal-strength concrete was identified to be 10% when combined with WGS, as it resulted in the highest increase in compressive strength after 28 days (Jagadesh et al., 2023; Wang et al., 2017). deduced that the compressive strength was highest when the fly ash replacement was 15%. Additionally, as the pore water saturation increased, the rebound value of the fly ash concrete first increased and then decreased. When the pore water saturation was below 20%, the rebound value continued to increase. However, the rebound value decreased significantly when the pore water saturation was between 20%–60%. Beyond 60% pure water saturation, the rebound value remained relatively stable. The water absorption and corrosion resistance capacity of marble powder-enhanced concrete revealed that the addition of ultra-hydrophobic marble powder decreased the concrete water absorption by 36.42% compared to conventional concrete. Electrochemical experiments revealed that the use of 20% super hydrophobic marble powder increased the polarization resistance of the mortar by  $4 \times 10^{-4}$  K $\Omega$ -cm<sup>2</sup> more than ordinary mortar, showing that the marble powder-based concrete could be helpful in offshore concrete structures (Song et al., 2022; Cao et al., 2023). Waste glass sludge, a silica-based industry, is also incorporated in concrete as a supplementary cementitious material. The superior mechanical characteristics of WGS (Waste Glass Sludge) are due to its increased pozzolanic reactivity, increased surface area, smaller particle size, and decreased overall porosity of the resulting concrete. It is important to use WGS with finer particle sizes to achieve optimal properties. The freezing and thawing resistance test results indicate that WGS has high durability, with a durability factor of over 90%. Additionally, the scaling resistance and rapid chloride penetration evaluation showed that WGS-contained concrete showed satisfactory results (Lee et al., 2018; Lu et al., 2019; Umar et al., 2022). Test results concluded by (Deng et al., 2023)

showed that using waste glass powder as a replacement for cement in concrete can improve the material's durability by forming a denser cement matrix through a pozzolanic reaction with lime during the early stages of hydration, resulting in the formation of additional C-S-H gel. Using glass particles in concrete can enhance its microstructure and decrease permeability, resulting in improved resistance to sulfate attacks and freeze-thaw cycles. However, it can also negatively affect carbonation resistance and increase the risk of ASR expansion. The extent of ASR expansion depends on the type, size, and amount of glass particles used. To mitigate the risk of ASR expansion, reducing the size of the glass particles is a simple and efficient solution. Glass particles smaller than 425 mm have been shown not to cause ASR expansion (Guo et al., 2020). Research (Ahmad et al., 2022) has shown that incorporating waste glass into rubberized concrete can significantly improve its mechanical performance, with a maximum improvement of 20% when using a 20% substitution rate. It was discovered that the concrete's compressive and split tensile strengths were 24% and 30% greater than those of ordinary concrete, respectively (Garg et al., 2023; Zeyad et al., 2020). Waste glass also improves the concrete's durability, including its resistance to water absorption, dry shrinkage, and acid. Experimental results by (Liu et al., 2016; Saba et al., 2021) confirmed that the strength of crumb rubber concrete made with pretreated rubber and synthetic resin increased by 12% for compressive strength, 40% for splitting tensile strength, and 5% for axial compressive strength. Additionally, the durability of the concrete was improved, as demonstrated by a reduced strength loss ratio of 1.2% after 25 cycles of freezing and thawing. Furthermore, the experimental analysis by (Xu et al., 2018) indicates that an increase in the rubber content of concrete leads to a greater number and longer cracks. This implies that the concrete is becoming more ductile, which allows it to absorb more energy during the collapse, making it more suitable for structures at risk of dangerous collapses (Meshram et al., 2023).

This study demonstrates that industrial waste materials like glass sludge and marble powder can be used as supplementary cementing materials when combined with crumb rubber to replace natural sand. To the authors' knowledge, this specific combination of three different industrial waste materials has not yet been studied. Using a sustainable performance model, economic and environmental factors were analyzed to determine the environmental impact of conventional concrete. Additionally, an optimization model utilizing the RSM method is presented to validate the study's findings, showcasing the research's uniqueness. Parallel to these studies, this research fulfills the research gap by investigating a wide range of factors such as compressive strength, flexural strength, split tensile strength, SEM, structural model; static analysis RSM; of the rubberized concrete (Table 1). Therefore, the researchers assumed the possibility of achieving that goal.

## 2 Materials and methods

### 2.1 Cement

Due to the low strength of recycled aggregates, it is necessary to increase the cement grade to improve the overall strength of rubberized concrete. This experiment used PO42.5 ordinary



**TABLE 1** author contribution table for studies.

Author	Rubberized concrete	Lab experiment	Compressive strength	Flexural strength	Split tensile strength	SEM	Structural model	Static analysis RSM	Methodology
Gerges et al. (2018)	Rubberized Concrete	√	√	√	√	×	×	×	Laboratory testing
Wang et al. (2022)	Rubberized Concrete	√	√	√	√	√	×	×	Laboratory testing
Alsaif et al. (2022)	Rubberized Concrete	√	√	√	√	√	×	×	Laboratory testing
Wang et al. (2022)	Rubberized Concrete	√	√	√	√	×	×	√	Laboratory testing
Zhang et al. (2023)	Rubberized Concrete	√	√	√	√	×	×	√	Laboratory testing
Hussain et al. (2019)	Rubberized Concrete	√	√	√	√	×	×	√	Laboratory testing
Ali et al. (2022)	Concrete	√	√	√	√	×	×	√	Laboratory testing
Tang et al. (2021)	Rubberized Concrete	√	√	√	√	×	×	√	Laboratory testing
This Research Work	Rubberized Concrete	√	√	√	√	√	√	√	Laboratory testing/SEM/structural model/Response Surface Method

**TABLE 2** Physical and mechanical properties of cement.

Density (g/cm <sup>3</sup> )	Coagulation time (min)		Flexural strength (MPa)		Compressive strength (MPa)	
	Initial coagulation time	Final coagulation time	3-day	28-day	3-day	28-day
3.15	190	260	5.0	8.5	24	51.2

**TABLE 3** Chemical composition of cementitious materials.

Chemical	CaO	SiO <sub>2</sub>	Na <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O	Fe <sub>2</sub> O <sub>3</sub>	SO <sub>3</sub>	TiO <sub>2</sub>	P. Size μm
OPC-Type 1	65	17.15	1.86	1.74	5.6	1.19	3.21	2.66	0.32	±20
Marble Powder	36.60	4.98	0.22	1.73	0.74	0.01	0.07	-	-	-

Portland cement, suitable for general industrial and civil buildings, produced by Pioneer Cement Co., Ltd. Its specific physical and mechanical properties are shown in Table 2 (Garg et al., 2023). The cement is a water-hard cementitious material, and the hydration reaction occurs after adding water; the main chemical reactions are the silicate hydration reaction and the aluminate hydration reaction. Cement composition is added in Table 3.

## 2.2 Reducing agents

To improve the workability of concrete and disperse cement particles more easily during mixing, reducing agents need to be

added. This article selects the high-efficiency reducing agent, whose basic performance parameters are shown in Table 4.

## 2.3 Coarse aggregate

The coarse aggregate is natural stone. The aggregate surface is uneven with many apertures, and many sizes. Due to the different shapes and sizes of natural stone, the particle size distribution is uneven. Therefore, the coarse aggregate should be crushed and sieved before being mixed with concrete (Liu et al., 2016). The internal porosity of the coarse aggregate is high, and the density is a little bit low. According to the classification standards for aggregates,

**TABLE 4** High-efficiency reducing agent parameters.

Inspection items	Net pulp flow (mm)	After 1 h, the net pulp flows (mm)	Solids (%)	Water reduction rate (%)	Compressive strength ratio (%)	Condensation time difference (min)	Shrinkage ratio (%)	Cl (%)	Secretion rate ratio (%)	Na <sub>2</sub> SO <sub>4</sub> (%)
Outcome	235	205	20.4	22.5	7 days; 125; 28 days; 120	Primary coagulation: ±120	115	0.015	54.0	0.2

**TABLE 5** Physical property parameters of coarse aggregate.

Apparent density (kg/m <sup>3</sup> )	Bulk density (kg/m <sup>3</sup> ) (Loose)	Bulk density (kg/m <sup>3</sup> )	Specific gravity	Water absorption (%)	Void ratio (%)	Fines modulus
2450	1350	1552	2.5	0.5	16	7

**TABLE 6** Physical Properties fine aggregate.

Apparent density (kg/m <sup>3</sup> )	Bulk density (kg/m <sup>3</sup> )	Specific gravity	Mud content (%)	Water absorption (%)	Fines modulus
2450	1450	2.6	0.25	1.57	3.2

it belongs to the lightweight aggregate category. The coarse aggregate particle size is graded between 5 and 20 mm and is continuously screened in this paper (Saba et al., 2021); the results are shown in Table 5.

## 2.4 Fine aggregate

The fine aggregate used in this study is natural sand from the river region of Pakistan. Natural sand has a well-graded particle size distribution, is classified as Zone II sand, and falls under the category of medium sand according to the fineness modulus. The physical properties of the sand used in this study were determined according to the “Experimental Regulations for Concrete” (Xu et al., 2018), with the results presented in Table 6. The rubber used in this study is tier rubber from the waste tier.

## 2.5 Specimens preparation

The investigation consisted of two phases. Initially, a model was optimized using Response Surface Method (RSM). The optimized results were validated in the second stage through a comprehensive experimental campaign. The study utilized a combination of fine aggregates with a size range of 0–4 mm, coarse aggregates with a size range of 4.75–10 mm, and Ordinary Portland cement (OPC) as the primary materials. In addition, crumb rubber with a size range of

0.221–0.35 mm was used. The mix design used in the experimental campaign is outlined in Table 7. The composition of the cement used is summarized in Table 7. A superplasticizer called Chemrite 520BA was also utilized. The study evaluated the concrete’s compressive, split, and flexural strength by testing at least 3 cylinders (300 × 150 mm) and 3 beams (100 × 100 × 500 mm) for each mix design composition.

## 2.6 Concrete production and testing phase

A standard concrete mixer was utilized to mix the concrete, and a vibrating Table operating at 350 Hz was employed to compact the concrete. The concrete ingredients were mixed in the following sequence: cement, waste glass sludge (WGS), marble powder, crumb rubber, natural fine aggregates, and coarse aggregates were added and dry mixed for 3 minutes to ensure a homogenous concrete matrix. Next, water and superplasticizer were added and mixed for 5 minutes before casting beams and cylinders. The compressive, split, flexural strength and microstructural analysis was carried out at 28 ± 3 days.

## 2.7 Response surface methodology

The response surface method (RSM) is an advanced statistical model showing several outcomes and responses for input variables.

**TABLE 7** Mix design of the concrete matrix in Kg/m<sup>3</sup>.

Mix ID	Cement	Fine aggregate	Coarse aggregate	Water	Marble powder	Waste glass sludge	Crumb rubber	Superplasticizer
SM-0	500	750	790	225	0	0	0	8.00
SM-1	480	750	790	225	20	0	0	8.00
SM-2	460	750	790	225	40	0	0	8.00
SM-3	440	750	790	225	60	0	0	8.00
SM-4	420	750	790	225	80	0	0	8.00
SWG-1	480	750	790	225	0	20	0	8.00
SWG-2	460	750	790	225	0	40	0	8.00
SWG-3	440	750	790	225	0	60	0	8.00
SWG-4	420	750	790	225	0	80	0	8.00
SMR-1	460	712.5	790	225	40	0	37.5	8.00
SMR-2	460	675	790	225	40	0	75	8.00
SMR-3	460	637.5	790	225	40	0	112.5	8.00
SMR-4	460	600	790	225	40	0	150	8.00
SWGR-1	440	712.5	790	225	0	60	37.5	8.00
SWGR-2	440	675	790	225	0	60	75	8.00
SWGR-3	440	637.5	790	225	0	60	112.5	8.00
SWGR-4	440	600	790	225	0	60	150	8.00

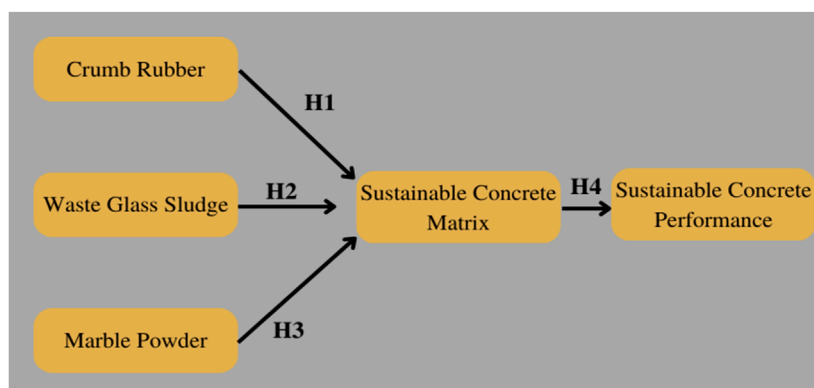
Where; SM (Marble content), SWG (Waste glass sludge), SMR (Marble Rubber), SWGR (Waste glass rubber).

The proposed method makes a polynomial relationship between the response and the input. This demonstration is helpful in the optimization of the mix design. The prediction models have been helpful for various purposes. For instance, (Rabczuk and Belytschko, 2004), suggested a prediction model for arbitrary cracks that addresses both 2D problems and experimental analysis.

Similarly, (Rabczuk and Belytschko, 2007), presented another 3D model for evaluating large deformations and cracks that help to analyze the available experimental data in 3D. To generate statistical data, it is essential to have relevant experimental data that helps to match the model and test results, which assists in checking the adequacy of the proposed model. Design-Expert v11 is a quantifiable computer program that features test plans, mathematical formulas, analytical research, and response improvement (Noordin et al., 2004; Akbar et al., 2023b). The ANOVA analysis tool is utilized to examine the relationship and effect of input components on the response (Myers et al., 1995).

## 2.8 Sustainable performance research methodology

Due to the increasing expansion of industrial activity, there are issues with waste generation, environmental contamination, resource scarcity, and deterioration of environmental condition (Ma et al., 2022). Construction industry looking for ways to switch from conventional to sustainable construction techniques to meet their economic objectives without causing environmental pollution (Oke et al., 2019). Therefore, we need sustainable materials to ensure sustainable performance. This is due to the growing environmental concerns, rising demand for construction materials, and the shortage of sustainable material supply. One major industry that requires more attention is construction because of its significant resource use, waste production, and environmental impact (Ma et al., 2023). The construction industry has a significant potential for improving the eco-friendly materials and technologies for sustainable performance (Ali et al., 2023). Moreover, Crumb rubber (CR), Waste glass sludge (WGS), and Marble powder (MP)



**FIGURE 1**  
Conceptual model.

makes a concrete mixture which influence the sustainable material performance. Therefore, reducing waste, improving energy, and resource efficiency are the three fundamental goals of the sustainable material. Based on above discussion and introduction we hypothesises that.

**H1:** Crumb rubber (CR) positively and significantly impacts the making of the sustainable concrete matrix (SCM)

**H2:** Waste glass sludge (WGS) positively and significantly impacts the making of sustainable concrete matrix (SCM)

**H3:** Marble powder (MP) positively and significantly impacts the making of sustainable concrete matrix (SCM)

**H4:** Sustainable concrete matrix (SCM) positively and significantly impacts sustainable material performance (SMP)

### 2.8.1 Data collection and procedure

The current research used a survey research design. A questionnaire was created to gather information and test hypotheses. To measure each concept, the questions from earlier literature are adopted. The survey questionnaire was examined for content validity, conformance to theoretical definitions, and redundancy by 21 academic professors and structural engineers with experience working on materials. Utilizing several techniques, the questionnaire's validity and reliability were guaranteed. Different portions of the questionnaire were used to represent the items for each construct. Each item is evaluated on a Likert scale of 1–7 points. In this study, the experts have experience working for organizations engaged in sustainable concrete and serve as the unit of analysis. Due to the target informant's excellent observations of sustainable concrete implementation in construction, a sample approach like this one was employed. The researchers selected a representative sample size of 21 for the statistical analysis. Figure 1 explain the structure model.

### 2.8.2 Measures and validation

For this study, the survey was divided into two portions. In the first part, fourteen items related to three dimensions of the

sustainable concrete matrix: crumb rubber, waste glass sludge, and marble powder. The crumb rubber was measured using four items. We adopt items for these parts from (Akbar et al., 2023b). The waste glass sludge was measured using five items. We adopt items for these parts from (Umar et al., 2022). Marble powder was measured using five items. We adopt items for these parts from (Ali et al., 2022). The final part calculated sustainable performance using environmental and economic dimensions. The environmental performance was measured using three items, and economic performance was measured using three items. The constructs for this part were derived from research (Li et al., 2019).

### 2.8.3 Data analysis

This study uses smart-PLS version 4 and partial least squares structural equation modelling (PLS-SEM). PLS-SEM is an effective method for examining intricate models. The study aims to identify endogenous variables contributing the least amount of variance to the model. PLS-SEM can simultaneously manage the structural and measurement models (Hair et al., 2019). The proposed model is tested with PLS-SEM. According to Hair (Hair et al., 2019), the measurement and structural models were explicitly approximated to produce reliable results, because this technique is most recommended when the goal of the study is to examine and predict the dependent variables in order to account for the maximum variance.

### 2.8.4 Measurement model analysis

We applied the validity and reliability tests Hair (Hair et al., 2019) recommended to evaluate the measurement model. Results above the 0.70 threshold were obtained when composite reliability and Cronbach alpha (CA) were used to evaluate the reliability of all constructs (Hair et al., 2019). The full results for AVE, CA, and CR values are shown in Table 8. To confirm the construct's validity, Petter advised computing first-order constructs' VIF and outer weight values (Petter et al., 2007). The outer and inner VIF values were less than 5.0, demonstrating the lack of multicollinearity in our data (Sarstedt et al., 2017; Fornell and Larcker, 1981). Additionally, the Heterotrait-Monotrait ratio (HTMT) and Fornell-Larcker criteria were used to evaluate the discriminant validity (DV)



TABLE 8 Reliability and validity.

Latent constructs	Factor loading range	CA	CR	AVE
<b>Sustainable concrete Matrix (SCM)</b>				
Crumb rubber (CRR)	0.723–0.876	0.857	0.869	0.639
Marble powder (MP)	0.751–0.881	0.899	0.828	0.597
WGS	0.763–0.869	0.806	0.814	0.721
<b>Sustainable Material performance (SMP)</b>				
Economic Performance (EF)	0.753–0.821	0.824	0.838	0.594
Environmental Performance (EEF)	0.794–0.872	0.901	0.911	0.654

TABLE 9 HTMT ratio.

	CR	EF	ENF	MP	WGS
CRR					
EF	0.604				
EEF	0.619	0.395			
MP	0.579	0.406	0.820		
WGS	0.403	0.393	0.715	0.717	

(Hair et al., 2019). Using a conventional approach, Fornell (1981) discovered that the AVE's root square value exceeded the correlation values in columns and rows. The HTMT is a more recent method of calculating DV; data indicates that all HTMT values were less than 0.85 (Henseler et al., 2015). As a result, the investigation's DV is unaffected. Tables 8 and, Tables 9 & Tables 10 present the complete collection of findings.

### 2.8.5 Structural model analysis

The structural model (Hussain et al., 2018) confirmed the underlying associations between independent and dependent variables (Hair et al., 2019). The study model was examined using its explanatory power ( $R^2$ ), predictive relevance ( $Q^2$ ), the goodness of fit (GOF), and  $\beta$  -values (path coefficients) values. Therefore,  $R^2$  values for dependent variables are typically low (less than 0.19), moderate (0.19–0.67), and substantial (above 0.67), predicted accuracy ratings. Based on the  $R^2$  values of 0.459 for sustainable performance, the model has a high degree of predictive power (Ansari et al., 2015; Ansari et al., 2016; Wajahat Sammer Ansari, 2017; Hair et al., 2019). The  $Q^2$  value for SPF was 0.443, indicating that endogenous variables were excellent because  $Q^2$  value is greater than zero (Hair et al., 2019). To assess the significance level of the coefficients, the t-value must be more than 1.96 and the p-value must be lower than 0.05. The findings show a significant and positive correlation between CRR, WGS, MP, and SCM, with beta values of 0.221, 0.362, and 0.371. As a result, our hypotheses H1, H2, and H3 are validated. Similarly, SCM shows a significant and positive

correlation with SPF, with  $\beta$  -value of 0.234 and a t-value of 9.663. As a result, our hypothesis (H4) has thus been validated as true (as shown in Table 11).

Finally, the GOF model measures how well the outer and inner measurement models predict the model's empirical results (Ansari et al., 2022). The formula used to compute the GOF is  $GOF = \frac{R^2}{1 + \sqrt{R^2}}$ ; PLS models have a global validation cutoff range of 0–1, which yields GOF big 0.36, medium 0.25, and tiny 0.1, respectively (Wetzels et al., 2009). The model's GOF is 0.510, which indicates that it has excellent predictive power and is a good fit for the data. SMP is a dependent variable in our model, with the following four antecedents predicting its occurrence: CR, WGS, MP, and SCM. SCM has a performance value of 65.774 and an importance value of 0.688, as shown in Figure 2. MP, CR, and WGS have performance values of 59.839, 64.016, and 64.709, respectively, and importance values of 0.282, 0.310, and 0.287.

## 3 Results and discussion

### 3.1 Compressive strength of marble powder, waste glass sludge and crumb rubber-based concrete

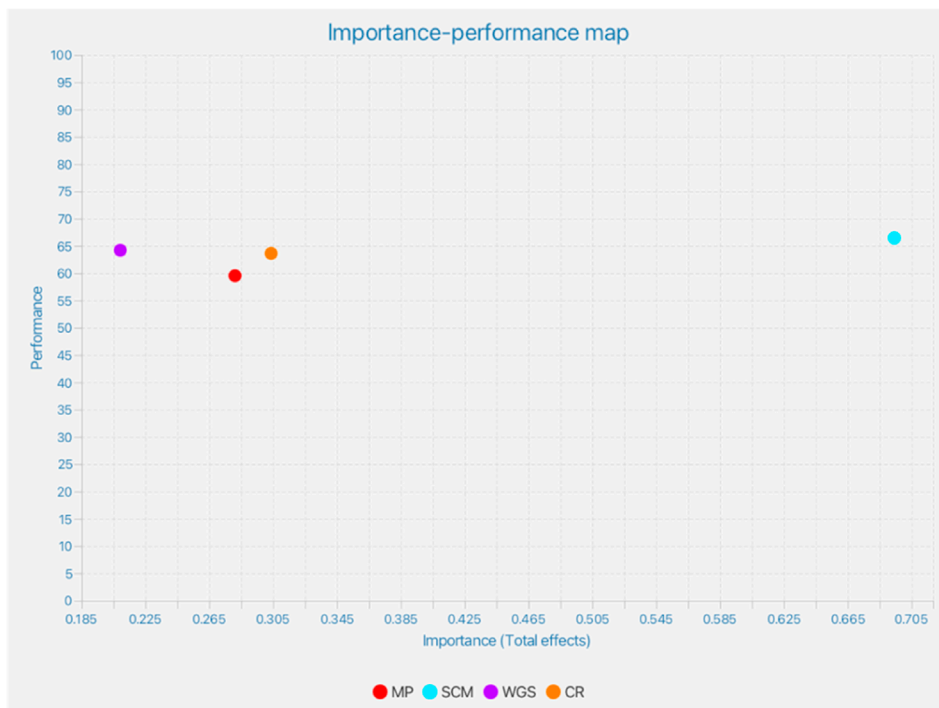
The compressive strength of concrete was evaluated with varying amounts of marble powder and compared to a control mix to determine the impact of marble powder on the concrete. Testing was conducted at ages 7, 14, 28, and 56 days. The results suggest a positive influence of marble powder at various ages. Marble powder replaced cement at dosages of 20, 40, 60, and 80 kg/m<sup>3</sup>. Figure 3 reveals compressive strength improved with cement replacement with marble powder up to 40 kg/m<sup>3</sup>. The maximum compressive strength, 34.6 MPa, was achieved at 56 days with the mix SMP-2, nearly equal to the control mix strength of 34.8 MPa. On the 28th day, the strength of SMP-2 showed a different pattern compared to the control and previous mix designs, which showed a slight decrease in strength, possibly due to a slower hydration process with marble powder. However, a decrease in strength was observed when the amount of marble powder was increased. At 56 days, mix designs SMP-3 and SMP-4 had strengths of 31.4 MPa and 27.3 MPa, respectively. During cement hydration, the growth of

**TABLE 10 Fornell-larcker criterion.**

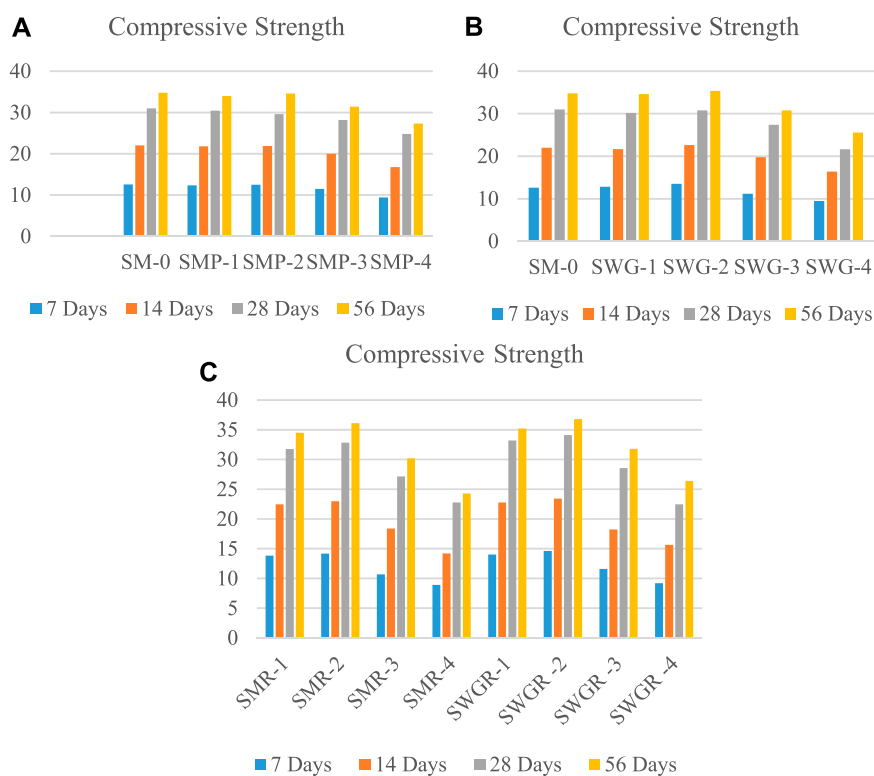
	Composite reliability	Economic factor (EF)	Environmental factor (ENF)	MP	WGS
CR	<b>0.838</b>				
EF	0.604	<b>0.810</b>			
EEF	0.619	0.395	<b>0.844</b>		
MP	0.579	0.406	0.820	<b>0.745</b>	
WGS	0.403	0.393	0.715	0.717	<b>0.829</b>

**TABLE 11 Formative construct evaluation and inner VIF.**

Latent constructs	Outer weight	t-value	p-value	VIF
<b>Sustainable Material performance</b>				
EF- > SMP	0.432	15.812	0.000	1.948
ENF- > SMP	0.331	12.472	0.000	2.771
<b>Sustainable concrete Matrix</b>				
CRR - > SCM	0.221	17.650	0.000	2.400
WGS - > SCM	0.362	15.190	0.000	2.819
MP - > SCM	0.371	13.223	0.000	2.742



**FIGURE 2**  
Importance of performance map analysis.



**FIGURE 3**

Compressive strength of the concrete (A) Marble-based concrete (B) Waste Glass Sludge concrete (C) Marble Powder, Waste Glass Sludge, and Rubber Concrete.

crystals on particle surfaces decreases cracks and pores. The particle size of marble powder impacts the microstructure of the hydration process. A large particle size provides structural support, while smaller particles can enter interior pores to enhance hydration. The results suggest that the proposed mix designs incorporating different percentages of marble powder are suitable for various concrete applications, minimizing the high dosage of cement (Santos et al., 2020; Wang et al., 2022).

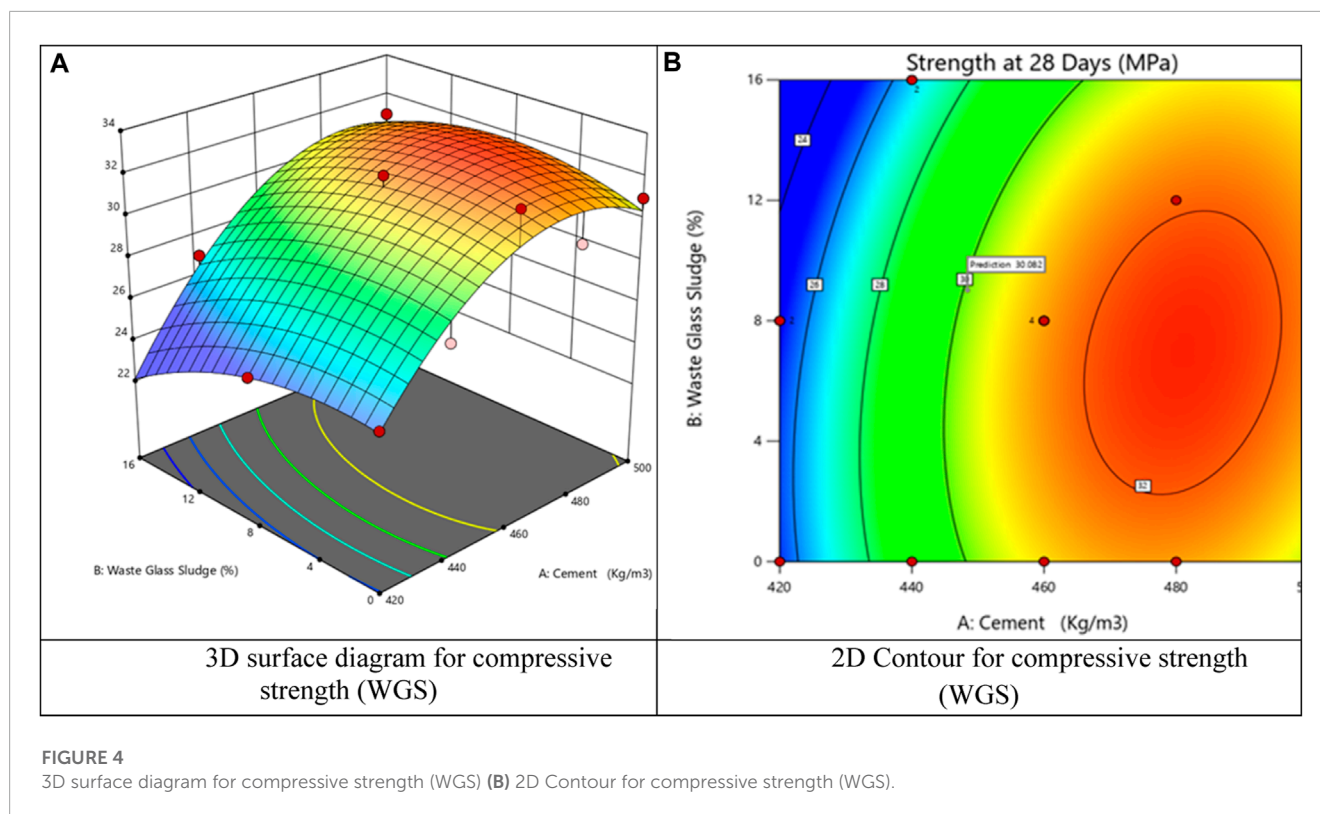
Concrete made with waste glass sludge had a higher compressive strength than that made with marble powder, as shown in Figure 3B. The strength improved gradually until a WGS replacement of 40 kg/m<sup>3</sup> was used, but it declined beyond that point. The highest strength was observed at 40 kg/m<sup>3</sup> WGS on the 56th day. The pozzolanic reaction in waste glass concrete was slower but increased over time and reached its maximum strength at a later stage.

Rubber, an inert material, doesn't participate in pozzolanic activities. However, rubber plays its role as a filler material. Figure 3C shows that concrete containing marble powder and crumb rubber improves the overall compressive strength. Replacing fine aggregate with crumb rubber up to 75 kg/m<sup>3</sup> improves the compressive strength to 32.82 MPa. Existing natural fine aggregates and crumb rubber played a better-filling role, improving the concrete matrix. For the higher content of crumb rubber, the strength of concrete is reduced, showing a disadvantage of a higher percentage of crumb rubber. However, the concrete strength of a later age improved due to the marble powder's slow hydration process. Waste glass sludge (WGS) and crumb rubber-based concrete outperformed the

marble powder and crumb rubber-based concrete specimens for the 28th and 56th days. This is because of the better pozzolanic activities of waste glass sludge than marble powder. SWGR-2, containing a waste glass sludge of 60 kg/m<sup>3</sup> and a crumb rubber of 75 kg/m<sup>3</sup> had a compressive strength of 36.8 MPa, the highest among all combinations. The 2D and 3D diagrams predicted by the RSM method suggested similar trends, as shown in Figures 4, 5.

### 3.2 Flexural and split tensile strength

The flexural strength of the concrete matrix is shown in the figure. Generally speaking, the flexural strength of concrete mainly depends on the conventional reinforcement or fibres, which helps to increase the flexural strength (Zaid et al., 2021). Besides, the reinforcement of the bonding of the concrete matrix also plays an important role. Glass powder, with its cementitious properties, showed promising results. In moderate incorporation, it has improved the mechanical strength of concrete (Mafalda and Sousa-coutinho, 2012). The test result of the current study shows similar results; a partial replacement of cement with marble powder and waste glass sludge showed better mechanical performance. At 56 days, the flexural strength of marble powder-based concrete reached a maximum of 3.4 MPa, while waste glass sludge-based concrete exhibited a maximum flexural strength of 3.38 MPa.



**FIGURE 4**  
 3D surface diagram for compressive strength (WGS) (B) 2D Contour for compressive strength (WGS).

Likewise, crumb rubber and crumb rubber-based concrete achieved a flexural strength of 3.4 MPa.

In contrast, waste glass sludge-based rubber concrete demonstrated a maximum flexural strength of 3.48 MPa at the same age of 56 days, as shown in Figure 6. The split tensile strength of concrete had similar trends, as shown in Figure 7. The 3D contour diagrams suggested by RSM predicted similar results, as shown in Figures 8, 9. The flexural and split tensile strength did not impact because of the addition of the supplementary cementitious materials. This indicates that cement can be partially replaced with marble powder and waste glass sludge. One of the fundamental reasons behind the enhanced strength properties of concrete with marble powder and waste glass sludge lies in their pozzolanic activity. Both marble powder and waste glass sludge contain high amounts of amorphous silica and alumina, which exhibit pozzolanic behaviour when in contact with calcium hydroxide (CH) released during cement hydration. This reaction forms additional calcium silicate hydrates (C-S-H) gel, filling the voids and pore spaces within the concrete matrix which ultimately decreases the porosity of concrete.

Consequently, the densification of the microstructure contributes to improved flexural and split tensile strength. The fine particles of these waste materials enhance the packing density of the concrete matrix, resulting in reduced porosity and increased interfacial transition zone (ITZ) density. This densification improves load transfer mechanisms and hinders crack propagation, leading to higher flexural and split tensile strength. Waste glass sludge typically contains alkaline components, such as sodium oxide and potassium oxide, which can act as chemical activators, promoting the early-age strength development of concrete.

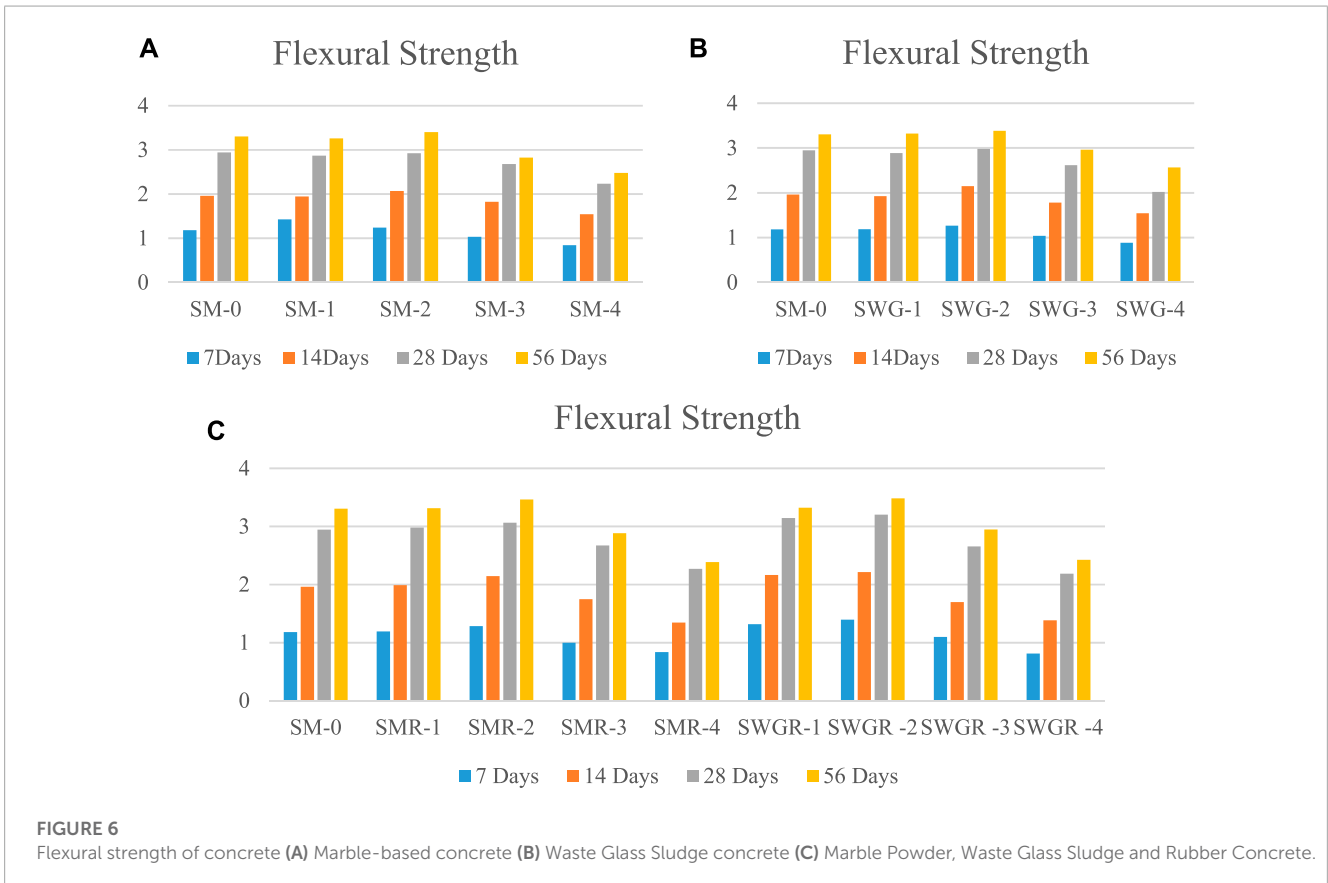
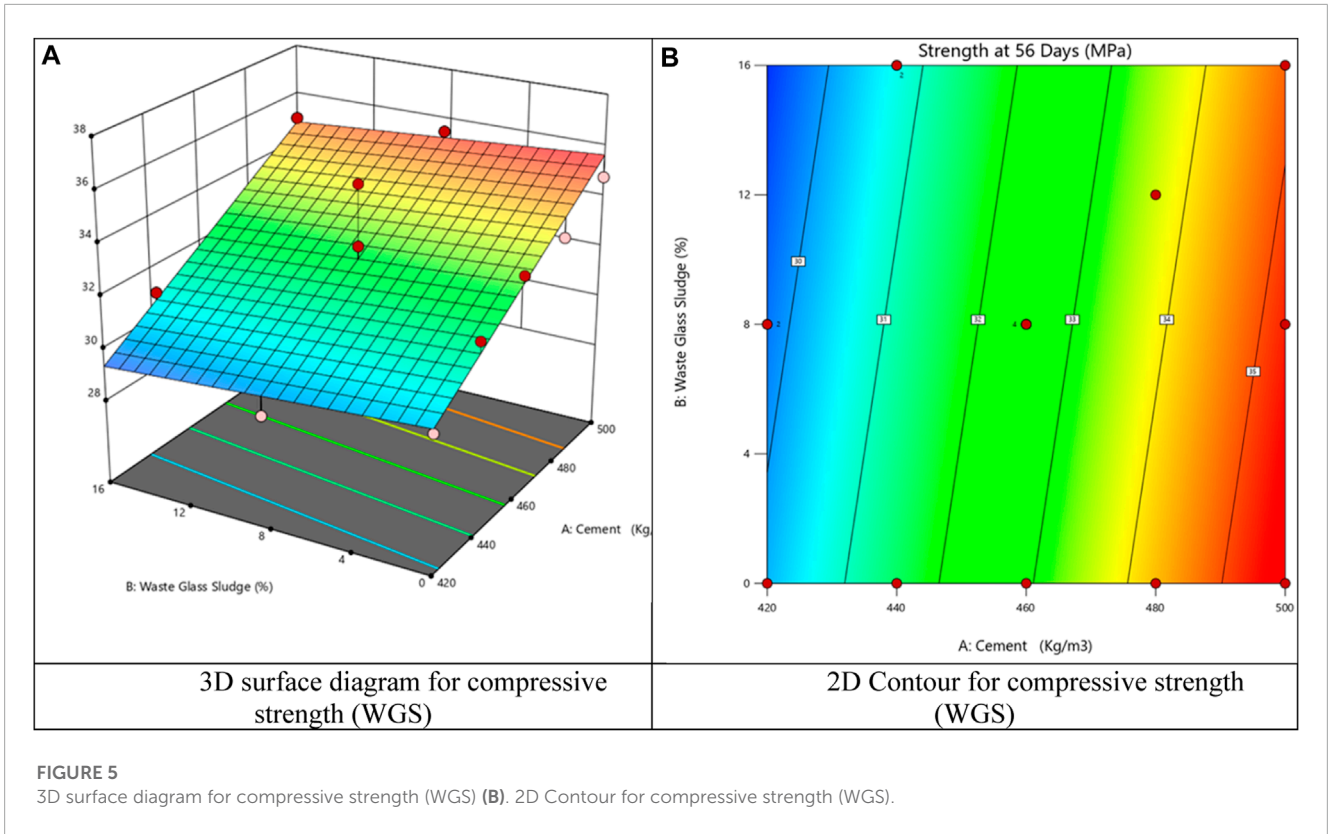
Additionally, the presence of these chemical admixtures can improve the homogeneity of the mix and reduce water demand, resulting in enhanced workability and subsequent strength gain. Marble powder and waste glass sludge incorporation can induce microstructural modifications within the concrete matrix. The fine particles of waste materials fill the gaps between cement particles, reducing the average pore size and enhancing the interconnectivity of the pore network. This microstructure refinement leads to increased strength, improved crack resistance, and a more durable concrete matrix. RSM results verify the experimental results, as shown in Figures 8, 9.

### 3.3 Structural model

In this study, a conceptual model (Hussain et al., 2018) that examines the relationship between sustainable concrete matrix and SMP is developed, which has received little prior study. We collected this study's information from the Pakistani construction industry to examine the hypothesis. According to empirical data, the sustainable concrete matrix inspired SMP to implement environmental and economic protection approaches. Our findings show that CR, WGS and MP significantly impact SCM with *t*-values (17.650, 15.190, and 13.223) which validate our hypotheses H1, H2, and H3. Finally, the sustainable concrete matrix significantly and positively affects SMP ( $\beta = 0.479$ ), validating hypothesis H4 (as shown in Table 12).

According to the results of this study, the sustainable concrete matrix is a valuable material that allows construction





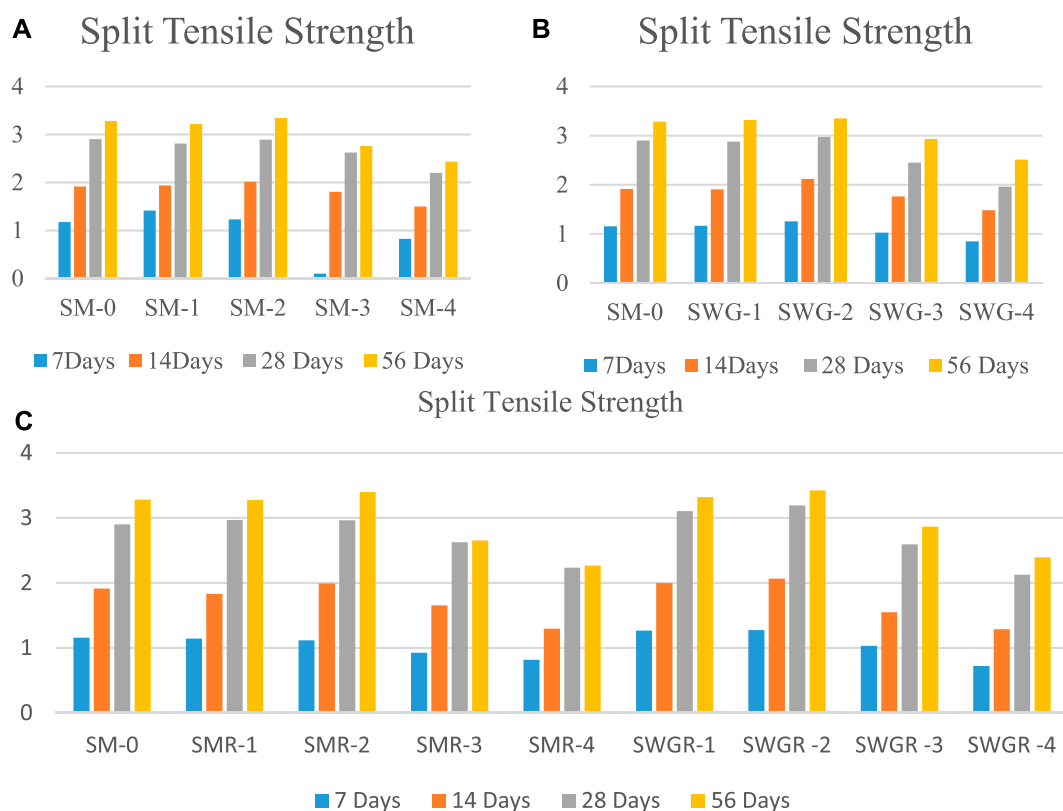


FIGURE 7

Split tensile strength of concrete (A) Marble concrete, (B) Waste Glass Sludge based concrete, (C) Marble Powder, Waste Glass Sludge and Rubber Concrete.

projects (Hussain et al., 2019) to achieve SD objectives by strengthening materials' economic and environmental influence. The findings of this research show that a sustainable concrete matrix improves SMP. As a result, we need to consider how important a sustainable concrete matrix is for accomplishing SMP.

### 3.3.1 Practical implications

The local cultural and ecological environment is under much pressure due to sustainable materials. To the best of our knowledge, this research is one of the first to analyze the influence of sustainable concrete matrix on sustainable material performance (SMP) comprehensively. It is remarkable that one of the sustainable initiatives, the sustainable concrete matrix, can, directly and indirectly, improve SMP. Therefore, structural engineers need to consider the positive impact of sustainable concrete matrix on sustainable delivery in a modest manner.

## 4 ANOVA analysis

This study examines the impact of three distinct variables, namely, a composite of 8% MP (B), 12% WGS (C), and 15% CR (D), on the strength of concrete (A). The statistical technique

of analysis of variance (ANOVA) was previously employed to determine the significance of the model. The statistical analysis reveals that the model's compressive strengths, measured at 36.8 MPa and 36.1 MPa, exhibit a significant difference with a  $p$ -value of 0.0003. The corresponding flexural strengths for the samples were 3.48 MPa and 3.42 MPa, while the split tensile strengths were 3.42 MPa and 3.29 MPa, respectively, as presented in Table 13. A statistical significance level, represented by a low  $p$ -value, indicates the suitability and pertinence of the model. The tabulated outcomes suggest that each of the models exhibits statistical significance. The probability of noise affecting the  $p$ -value of the model is 0.0003. Models that possess  $F$ -values below 30.17 are deemed indispensable. Table 7 presents the results.

To determine the validity of the models, the coefficient of determination, also known as R-squared ( $R^2$ ), must lie within the range of 0.8824–0.9904. Both models exhibit a variance of less than 0.1 for both adjusted  $R^2$  and projected  $R^2$ . This implies a reasonable level of consistency between the modified  $R^2$  and the projected  $R^2$ . The signal-to-noise ratio measurement is deemed a prerequisite for achieving optimal accuracy. Table 6 demonstrates that all models can traverse the design space. A method for model validation involves generating a 2D contour plot from a 3D surface diagram. It has been observed that when the points are nearly parallel to the normal line, the predicted value yields

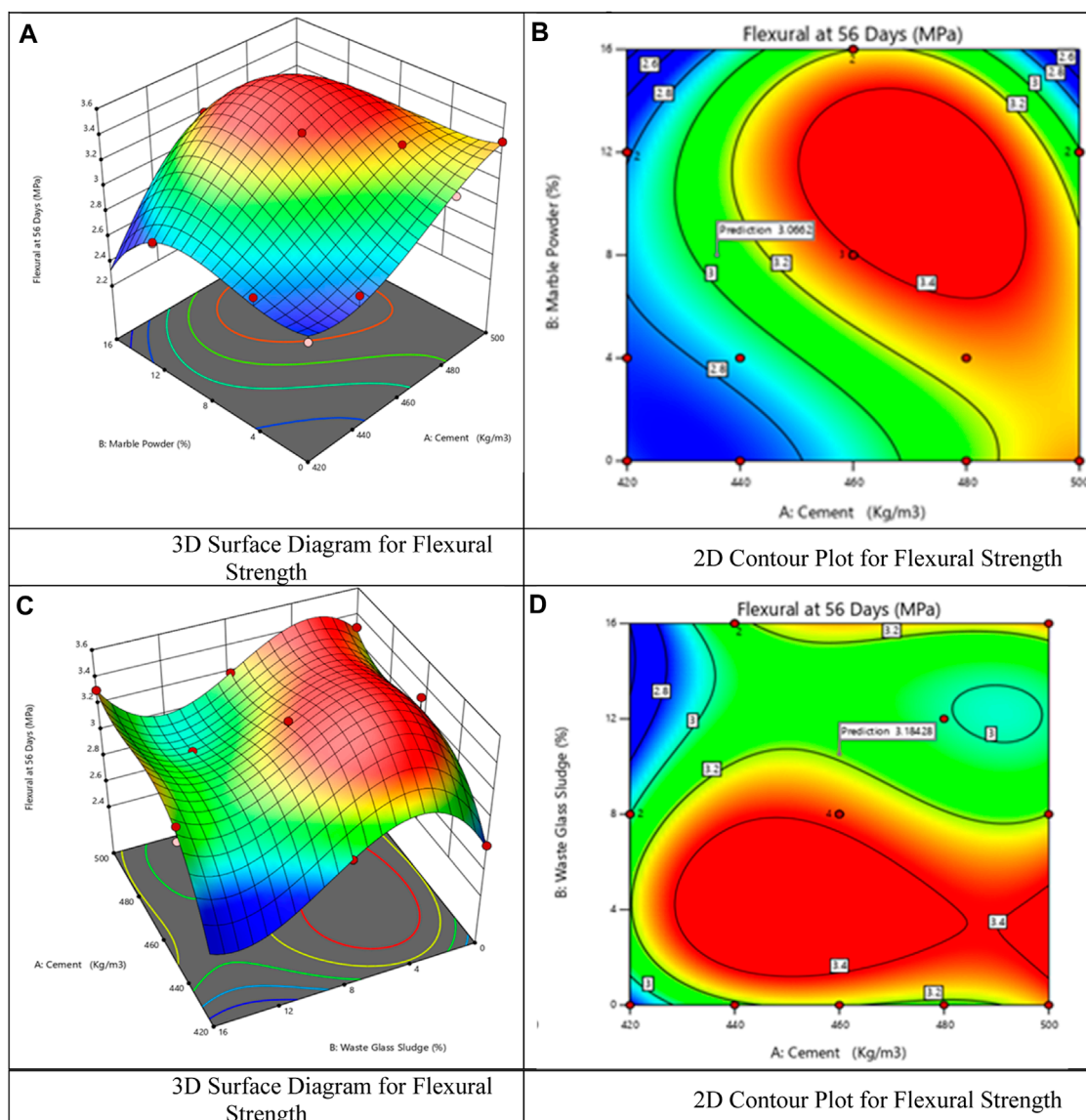


FIGURE 8

(A). 3D surface diagram for flexural strength (B). 2D contour plot for flexural strength (C). 3D surface diagram for flexural strength (D). 2D contour plot for flexural strength.

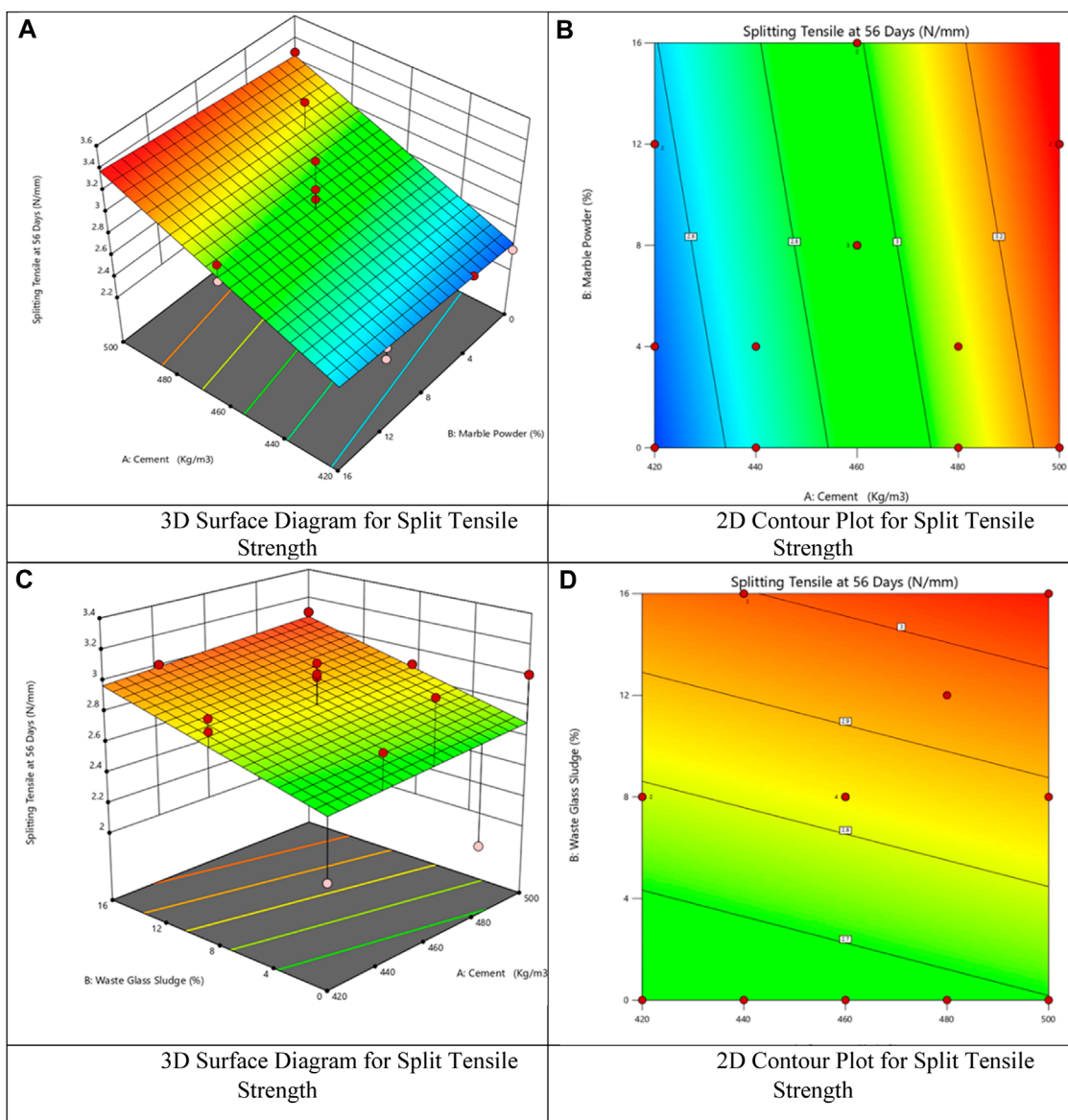
more precise outcomes than anticipated (Akbar et al., 2023a). The model's validity and ability to select optimal extraction parameters based on response outcomes are determined using normal residual plots.

Using response surface method (RSM), the interaction of three factors, marble powder, glass sludge, and rubber particles, on mechanical strength was modelled. When all data from the first mixture has been successfully collected, 21 distinct mixture designs are developed based on the first RSM mixture design and re-entered into the RSM to verify their efficacy, resulting in the final model, as shown in Table 14. The comparative outcomes indicate that the results obtained from the experiment and Response Surface Method (RSM) are comparable and satisfactory. The study reveals that the desired value is 0.592, which suggests

that 36.8 MPa and 36.1 compressive strengths can be realized by utilizing 12% WGS, 15% rubber, and 8% MP. The flexural strength values for the samples were 3.48 MPa and 3.42 MPa, while the split tensile strength values were 3.42 MPa and 3.29 MPa, respectively.

## 5 Microstructure analysis

Marble powder contains calcium carbonate mineral content equivalent to ground limestone reactivity found in cement. Its presence in the concrete mix increases early compressive and flexural strength gains via internal curing effects caused by the hydrolysis reaction of free lime leaching out of the calcined



**FIGURE 9** (A). 3D surface diagram for split tensile strength (B). 2D contour plot for split tensile strength (C). 3D surface diagram for split tensile strength (D). 2D contour plot for split tensile strength.

**TABLE 12** Hypothesis testing results.

	Hypothesized path	$\beta$ -value	t-value	p-value	Decision
H1	CR- > SCM	0.221	17.650	0.000	Accepted
H2	WGS- > SCM	0.362	15.190	0.000	Accepted
H3	MP- > SCM	0.371	13.223	0.000	Accepted
H4	SCM->SMP	0.234	09.663	0.000	Accepted

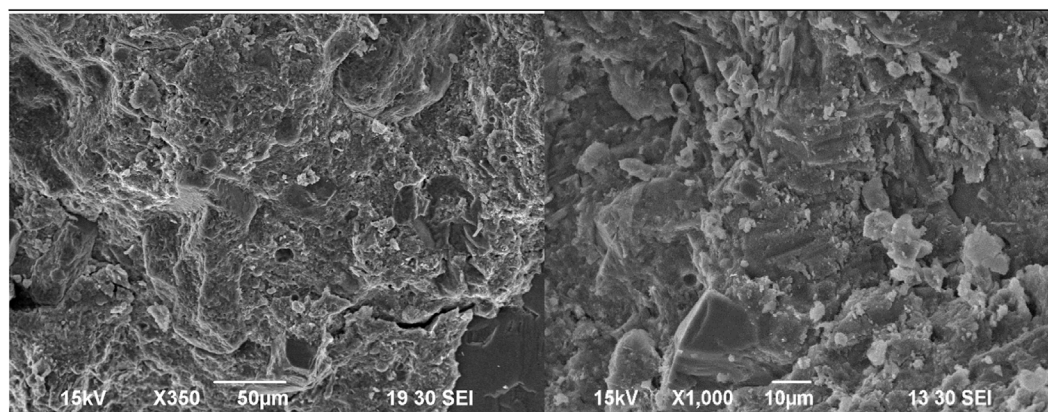


TABLE 13 ANOVA analysis of the response models.

Model	Source	Sum of squares	df	Mean square	F-value	p-value	Significance of the model
Compressive Strength	Model	118.34	9	13.15	30.17	0.0003	significant
	A-Cement	16.03	1	16.03	36.77	0.0009	significant
	B-Marble Powder	3.34	1	3.34	7.67	0.0324	significant
	C-Waste Glass Sludge	4.81	1	4.81	5.22	0.0345	significant
	D-Tier Rubber (%)	8.73	1	8.73	49.74	0.0004	significant
	Residual	123.08	26	4.73			
	Lack of Fit	120.02	11	10.91	53.44	<0.0001	significant
Split Tensile Strength	Model	1.29	2	0.6440	15.44	0.0004	significant
	A-Cement	1.23	1	1.23	29.51	0.0001	significant
	B-Marble Powder	0.0330	1	0.0330	0.7910	0.3900	significant
	C-Waste Glass Sludge	0.0239	1	0.0239	0.9029	0.3608	significant
	D-Crumb Rubber	1.04	9	0.1150	5.80	0.0222	significant
	Residual	4.09	11	0.3722	6.83	0.0241	
	Lack of Fit	10.34	14	2.08			
Flexural Strength	Model	0.8897	9	0.0989	7.50	0.0117	significant
	A-Cement	0.0179	1	0.0179	1.36	0.2880	
	B-Marble Powder	0.0131	1	0.0131	6.87	0.0396	
	C-Waste Glass Sludge	0.0389	1	0.0389	3.52	0.1097	
	D-Tier Rubber (%)	0.0282	1	0.0282	35.47	0.0010	
	Residual	4.09	11	0.3722	6.83	0.0241	
	Lack of Fit	10.34	14	2.08			

TABLE 14 Models' validation.

Model Terms	Cement + waste glass sludge + tier rubber			Cement + marble powder + tier rubber		
	Compressive Strength	Split Tensile Strength	Flexural Strength	Compressive Strength	Split Tensile Strength	Flexural Strength
Mean	32.46	2.81	3.18	32.38	2.89	3.06
Std.Dev	1.09	0.0454	0.0864	0.3355	0.0242	0.0649
R <sup>2</sup>	0.8824	0.8838	0.8991	0.9904	0.9038	0.9752
Adj. R <sup>2</sup>	0.8489	0.8287	0.8477	0.9759	0.8582	0.9379
Pred. R <sup>2</sup>	0.8140	0.8062	0.8243	0.9124	0.8278	0.8842
C.V %	3.36	2.27	2.72	1.04	2.06	2.12

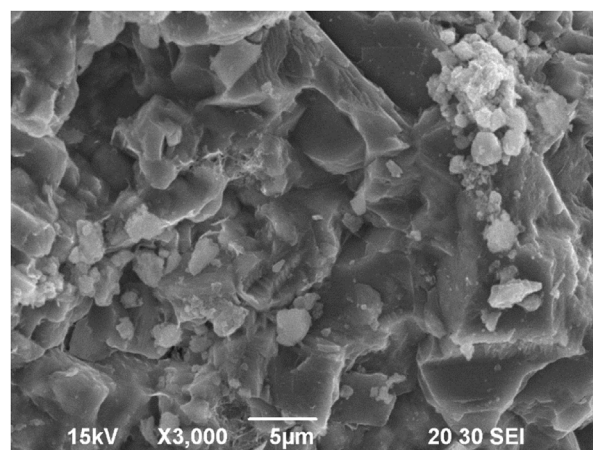


**FIGURE 10**  
Marble powder reactivity in concrete matrix at 28 days.

powder. Improvements extend beyond the matrix to reinforced structural elements where bond efficiency can improve due to advanced interfacial transition zone behavior between steel bars and their surroundings now containing reactive marble fragments as nonmetric secondary particles dispersed homogeneously within the paste. Consequently, applying marble dust results in stronger hardened concrete. The higher compressive strength was due to the better filling capacity of marble waste powder. The reactivity at different hydration days is shown in Figure 10 of marble powder. By focusing on Figure 10, it is evident that marble powder acts as a filler, and its pozzolanic reactivity is efficient. After 28 days of hydration, the surface of the concrete matrix becomes dense by agglomeration of crystals (Wang et al., 2022). The marble powder fills the voids in the concrete matrix and thus acts as micro fillers. These micro fillers mix results in higher densities, low workability, and higher compressive strengths. However, their high dosage can result in lower density and porous microstructure as compared to conventional concrete. The glass sludge showed pozzolanic behaviour as silica present in glass can react with calcium hydroxide, finally giving calcium silicate hydrate gel (C-S-H). This pozzolanic reactivity Leads to increased compressive strength (Zheng, 2016).

Focusing on Figure 11, waste glass sludge incorporation of cement-based materials concludes to be a very dense structure. This dense structure is mostly due to the formation of calcium silicate hydrate gel (C-S-H) (Umar et al., 2022). CSH gel comprises amorphous primary phases. However, glass sludge has a drawback: it reduces density and can result in a porous matrix. This matrix can be solved by incorporating crumb rubber and marble powder fillers. Besides, waste glass and marble powder both work as densification. Crumb rubber, marble powder, and waste glass are filler materials. By incorporating crumb rubber, we reduce the need to extract new raw materials and decrease waste sent to landfills.

Additionally, producing new concrete without crumb rubber means less greenhouse gas emissions related to transporting and processing construction materials (Xu et al., 2018). Therefore, SCM samples have optimum crumb rubber, marble powder, and waste glass sludge incorporation. Which ultimately leads



**FIGURE 11**  
Waste glass sludge incorporation in cement at 28 days of hydration.

to sustainable concrete matrix having high tensile, compressive, and flexural strengths. The better mechanical strengths, densification, and packed structure manifest its sustainable concrete performance, and thus, the name is given as a sustainable concrete matrix.

## 6 Conclusion and recommendations

This study examined the mechanical characteristics of environmentally friendly rubberized concrete produced using marble powder, waste glass sludge, and crumb rubber. In the experiment, a portion of the fine aggregates was substituted with crumb rubber (CR), and the cement was replaced with marble powder and waste glass sludge. The findings lead to the following conclusions.

- Test results show the positive influence of the marble powder and waste glass sludge incorporation in the concrete matrix as it helps in the formation of C-S-H and also acts as a filler material. Adding marble powder, waste glass sludge, and crumb rubber positively impacted compressive, flexural, and split tensile strength.
- This analysis conducted a two-way ANOVA with a significance of the model of less than 0.001. The residual error resulting from the lack of fit and pure error was found to be minimal. The predictive model accurately captures the relationship between the variables and the response.
- The RSM model for determining sustainable concrete's compressive, split tensile, and flexural strengths yielded satisfactory results. However, further investigation is required to establish a regression relationship between aggregates and rubber concrete. This relationship would enable the RSM model to make accurate predictions in future applications.
- To tackle the environmental concerns associated with crumb rubber derived from waste tires, utilizing automobile tires and replacing cement with marble powder and waste glass sludge in concrete can be an effective solution. This approach not only enhances the durability of concrete but also proves to be cost-effective, aligning with the United Nations' Sustainable Development Goals. Additionally, substituting crumb rubber waste tires for natural fine aggregate and replacing cement with marble powder and waste glass sludge aids in reducing cement consumption, thereby contributing to a decrease in carbon emissions.
- This sustainability model contributes to knowledge by exploring the link between sustainable concrete matrix (SCM) and sustainable development (SD) in construction. Hypotheses were tested using SEM, and existing literature informed the study's framework. Findings emphasize the significance of SCM for achieving sustainable materials goals, aiding organizational excellence, and SD in the construction industry. Besides, it helps minimize cement-based industries' environmental impacts by incorporating supplementary cementitious materials.

## 6.1 Recommendations

The results presented in this study indicate that refuse glass slurry and marble powder are more dependable predictors of potential mechanical properties of concrete, particularly sustainable concrete, which is the primary objective of environmentally friendly concrete. Nevertheless, its utilization ought to be approached

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with prudence and in conjunction with established dependable calibrations. According to the findings, mechanical properties and RSM provide greater statistical confidence than conventional concrete. A mixture of 8% marble granules and 12% refuse glass slurry by weight can be utilized effectively in place of cement. 15% of the natural sediment is substituted with crumb rubber to produce sustainable concrete.

## Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: Shall be provided upon request.

## Author contributions

MAk: Methodology, Software, Writing–review and editing. ZH: Conceptualization, Data curation, Formal Analysis, Writing–original draft. MI: Formal Analysis, Data curation, Software, Supervision, Writing–review and editing. SB: Investigation, Project administration, Writing–review and editing. MAN: Conceptualization, Formal Analysis, Writing–review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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