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# Investigating the governing factors influencing the pozzolanic activity through a database approach for the development of sustainable cementitious materials

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A B S T R A C T

Pozzolans, known to possess high pozzolanic activity, enhances the long-term engineering properties of concrete due to the consumption of calcium hydroxide and the consequent formation of the calcium-silicate-hydrate gels within the cementitious matrix. Although the key factors that affect the pozzolanic activity such as the chemical composition, amorphousness, and fineness are commonly addressed in literature, there is a growing need to further gain an insight into the factors that govern this activity in a more comprehensive approach. The aim of this empirical study is to develop concrete models comprising optimal replacement of pozzolans based on the governing factors affecting the activity through the database approach. The database, consisting of 631 number of data points harvested from the literature, is established to determine the optimum replacement levels of the designated pozzolans in concrete. The governing factors therefore played a key role in establishing the boundary conditions that enabled the potential concrete models to be generated particularly for the sustainability assessment of concrete incorporating pozzolans. The study shows that the optimum replacement levels in concrete mixtures are 15–50% for GGBS, 10–35% for fly ash, and 5–15% for silica fume. The study furthermore demonstrated that the utilisation of these substitutions leaded a considerable reduction in carbon emissions that ranged from 13% to 43% for GGBS, 9–31% for fly ash, and 4–13% for silica fume. The study significantly contributes to the generation of greener construction materials, and offers a cleaner disposal route for the pozzolans principally compared to the traditional waste management alternatives.

## 1. Introduction

Over the last century, the structural superiority of mega buildings, the rapid growth of the construction industry, and rampant urbanization have led to an increased need of Portland cement in the building industry, and consequently, cement has become one of the most widely used and produced building materials worldwide [41]. It is widely reported that the high energy intensity nature of clinker (cradle to grave approach) caused Portland cement to be one of the leading contributors to global warming and $CO_2$ emissions. Recent studies indicated that cement production is estimated to be responsible for 12–15% of all industrial energy consumption and approximately 5% of all anthropogenic $CO_2$ emissions [41]. Portland Cement Association (2022) [89] revealed that one ton of cement produces 0.9 tons of $CO_2$ from extraction to the field. It is an alarming concern to alleviate the detrimental effect of rapid

*Abbreviations:* Al2O3, Aluminum oxide; ASTM, American Society for Testing and Materials; BS, British Standards; CaCO3, Calcium carbonate; CaO, Calcium oxide; CaOH2, Calcium hydroxide; CO2, Carbon dioxide; CSc, Compressive Strength; C-S-H, Calcium silicate hydrate; EG, Glass E; EN, European Norm; FA, Fly ash; Fe2O3, Ferric oxide; GGBS, Ground Granulated Blast Furnace Slag; GHG, Greenhouse Gas; IEA, International Energy Agency; ISSA, Sewage sludge ash; KG, Glass K; LCA, Life cycle assessment; MK, Metakaolin; NF, French Norm; OPC, Ordinary Portland Cement; PFA, Pulverized Fuel Ash; PPC, Portland Pozzolana Cement; RBD, Red Brick Dust; RHA, Rice Husk Ash; RHC, Rapid Hardening Cement; SAI, Strength Activity Index; SCBA, Sugar cane bagasse ash; SCMs, Supplementary Cementitious Materials; SF, Silica fume; SSA, Specific surface area; SiO2, Silicon dioxide; VAF, Ultra-fine volcanic ash; XRF, X-Ray Fluorescence.

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**Nomenclature**

| | |
|---|---|
| °C | Degrees Celsius. |
| g | Gram. |
| h | Hour. |
| mg | Milligrams. |
| ml | Milliliters. |
| MPa | Mega Pascal. |

cement consumption that has an adverse effect on global warming.

Pozzolans are known to possess high pozzolanic activity that enhances the long-term engineering properties of concrete due to the consumption of calcium hydroxide and the consequent formation of the calcium-silicate-hydrate gels within the cement matrix [42]. There is a large volume of published studies in the literature addressing the factors affecting the pozzolanic activity [12,19,2,48]. Although these factors range from water content, chemical composition, fineness, morphology, specific surface area, amorphousness, water to binder ratio, calcium oxide content ([61,67]; Walker and Pavia, 2010; Harrison, 2019), in this study, four major governing factors namely; fineness, silica-alumina-iron content, calcium oxide content, and water-to-binder ratio, are designated based on the reported knowledge in the literature and their influence in the cementitious matrix is further investigated in this study.

There are numerous studies in the literature addressing the significances of fineness of pozzolans on the pozzolanic activity and consequently the affirmative influences on the mechanical properties and durability of cementitious matrix [48,86]. The increase in fineness improves the filling ability, passing ability and segregation resistance of pozzolans in the matrix and hence results in a significant reduction of the porosity that yields to increased pozzolanic activity within the cementitious materials [98,11]. The increase in the pozzolanic reactivity along with the enhancements in filling in micro-spaces then resulted in the vital increases in the mechanical properties of such materials particularly the compressive strength of cement-based materials [100,48,67].

$SiO_2$ (Si), $Al_2O_3$ (Al), and $Fe_2O_3$ (Fe) contents have been another influential factor of pozzolanic activity and its positive impact on mechanical performance pointed out by various researchers in literature ([98]; Habert, 2008, Bumaris et al., 2020; [95,67]). A chemical reaction between the four oxides $SiO_2$, $Al_2O_3$, $Fe_2O_3$, and CaO reported to increase the calcium silicate hydrate (C-S-H) gel formation and consequently enhance the mechanical performance of concrete [36]. In line with this, Walker and Pavía [95], Habert et al., [35], Záleská et al., [98], and Mohammed [67] put forth that increasing the amount of Silica, Alumina, and Iron, specifically in their amorphous phase yields to a smooth pozzolanic reaction. Bumanis et al., [15] also demonstrated that the increase in the total amount of Si, Al, and Fe content considerably affects the compressive strength of concrete comprising pozzolans.

It is also widely reported in the literature that the properties and the replacement levels of the pozzolans influences the required water to binder ratio of the mixture for the essential strength development of concrete. For instance, while Kaminsky et al., (2020) [46] stated that fly ash and ground glass pozzolans require a low water-to-binder ratio, much finer particle size of silica fume and metakaolin demand large amounts of water to attain equivalent consistency and strength development of such matrix. Similarly, Moffatt et al., [63] found that the water-to-binder ratio of high-volume fly ash concrete should not exceed 0.40. It is also widely reported in the literature that both the composition of the binder and the water to cement ratio have influenced the durability characteristics such as level of chloride penetration and surface deterioration [90]. The best resistance to chloride infiltration is attained in concrete with a water to cement ratio of $\leq$ 0.40 and slag replacement between 45% and 65%. Also, Thomas and Bremner [90] revealed that the resistance of high-performance concrete against chloride ion penetration can be improved with silica fume incorporation at a low water to cement ratio.

According to Harrison (2019), calcium hydroxide ($CaOH_2$) is being produced in the matrix during the reaction between water and the free lime (CaO) that is naturally present in cement clinker. It is a well-known fact that cement contains about 60% CaO in its chemical composition and its influence on the pozzolanic reaction is reported in the literature (Bumaris et al., 2020; Kaminsky et al., 2020) [15,46]. For instance, the study reported by Bumaris et al., (2020) showed that pozzolan with higher CaO content yielded a greater mechanical performance even though Si, Al, and Fe content were lower than required by ASTM C618–22 standard. Similarly, a study by Kaminsky et al., (2020) [46] demonstrated that mortars comprised Class C type of fly ash resulted in greater pozzolanic activity compared that of the Class F type despite much higher silica, alumina, and iron content in its mineralogy. This finding is attributed to the higher free CaO content of Class C type of fly ash as well as the amorphous phase of silica. Tangadagi et al., [88] further explains that the ultrafine particles of pozzolans improve the concrete strength by reacting with excess lime, CaO to form calcium-silicate-hydrate, C-S-H, gel that results in denser, stronger, and less porous concrete. It must also be noted that the blast furnace slag which contains 40% CaO and pre-heat-treated oxides, requires less energy for cement clinker manufacture [36].

Durability of cementitious matrix is also known to be enhanced by the use of pozzolans. It is widely reported in the literature that the utilisation of pozzolans significantly improves the abrasion resistance, resistance to oxygen penetration, water absorption and chloride permeability ([8,30,57,97]; Kartik Reddy et al., 2013). The enhancement attained in durability characteristics of cementitious materials comprising pozzolans are mainly due to the consumption of calcium hydroxide which is more prone to be attacked by physical and chemical actions due to its weaker nature in the structure and consequently the formation of the additional calcium-silicate-hydrate gels that are primarily responsible from the strength development of the matrix. The further formation of calcium-silicate-hydrate gels do not only result in the enhanced strength development but also yields to a more consolidated cementitious matrix and hence results in a reduced permeability and absorption that improves the durability of such systems considerably [45,75,86]. Table 1(a) and (b) summarize the recent available extant literature on pozzolanic activity and hence report the parameters covered as well as provide highlights and conclusions.

There are numerous studies in the literature addressing the advances of the utilization of pozzolans for the development of sustainable building materials primarily through the reduction of energy consumption attained during the cement production [12,21,60,77,80]. For instance, Manjunatha et al., [60] stated that GGBS and Portland Pozzolana Cement (PPC) results in a reduced adverse effect on climate as a consequence of the reduction in $CO_2$ emissions, human health effects and resource depletion. Similarly, Radwan et al., [77] acquired 40–55% environmental damage reduction through the use of GGBS and fly ash as replacement in cement. Pradhan et al., [74] also reported significant reductions on the global warming potential as a result of the utilization of fly ash, and GGBS. based on his research, using fly ash at 30%, GGBS at 50%, and LC at 3% reduces the GWP compared to the controlled mix by around 23%, 34%, and 44%, respectively. Overall, waste pozzolan incorporation shows a great reduction in carbon emission and general human toxicity, which contributes the greener production of construction materials. Table 2 demonstrates a summary of recent life cycle analyses of various pozzolanic materials including methodologies and the major outcomes.

This study presents the extensive database analysis of the designated pozzolans, silica fume, GGBS and fly ash and their utilization in concrete applications. The significance of this study is that it investigates the mechanical and environmental performance of designated pozzolans

**Table 1**
(a): Extant literature on pozzolanic activity.

| Year | Author (s) | Name of the paper | Aim of the paper | Parameters covered | Highlights and Conclusion |
|---|---|---|---|---|---|
| 2015 | P. Sargent [80] | Handbook of Alkali-Activated Cements, Mortars and Concretes | The development of alkali-activated mixtures for soil stabilization. | ✓ Particle size distribution,<br>✓ Surface area/ reactivity,<br>✓ Mineralogical,<br>✓ Chemical characteristics. | Industrial by products (alumina-silicate based) have great potential as sustainable replacement. |
| 2015 | Ferraz, E. [27] | Pozzolanic activity of metakaolin | Modified Chapelle test as a direct laboratory methodology to access the pozzolanic activity. | ✓ $Ca(OH)_2$ content,<br>✓ Specific surface area,<br>✓ XRD patterns. | The modified Chapelle pozzolanic activity is independent of the particle morphology,<br>The grinding stage significantly affects the modified Chapelle pozzolanic activity,<br>No relation either with specific surface area or calcined kaolinite morphology to modified Chapelle pozzolanic activity. |
| 2016 | Black, L. [12] | Low clinker cement as a sustainable construction material | SCMs, their origins, composition, and physical properties. | ✓ Durability options for chemical attacks,<br>✓ Environmental Parameters (LCA). | The use of SCMs in concrete is an efficient means of reducing the environmental burden of construction,<br>reducing embodied carbon,<br>reducing abiotic depletion,<br>option for waste material from landfills. |
| 2017 | Mohammed, S. [67] | Processing, effect, and reactivity assessment of artificial pozzolans obtained from clays and clay wastes: A review. | An overview of the literature related to the elaboration, the utilization, the efficiency and the pozzolanicity tests. | ✓ ($SiO_2 + Al_2O_3 + Fe_2O_3$) content,<br>✓ Dihydroxylation (amorphousness) degree,<br>✓ Fineness. | Three factors affect pozzolanic reactivity:<br>($SiO_2 + Al_2O_3 + Fe_2O_3$) content,<br>its dihydroxylation (amorphousness) degree,<br>the fineness of its particles.<br>Mechanical method is the least efficient because it considers both pozzolanities: chemical and physical. |
| 2019 | McCarthy, M. J., & Dyer, T. D. [61] | Pozzolanas and Pozzolanic Materials | Pozzolans' influences on the properties of concrete, including fresh, mechanical, and chemical/physical aspects of durability. | ✓ Particle Size Distribution,<br>✓ Modulus of Elasticity,<br>✓ Compressive Strength,<br>✓ Tensile Strength,<br>✓ Shrinkage and Creep. | Fly ash, depending on its characteristics, can reduce the water requirement of concrete,<br>For some of the higher fineness pozzolanic materials, the opposite may occur, and the use of super plasticizing admixtures may be a necessary part of their adoption,<br>Longer-term strength enhancements are achievable for pozzolans. |
| 2019 | Ahmed, A. [2] | Chemical Reactions in Pozzolanic Concrete | Elaboration on the different types of chemical reactions taking place in concrete containing pozzolans as a partial cement replacement. | ✓ Hydration reaction,<br>✓ Durability,<br>✓ Chemical parameters,<br>✓ Mechanical parameters. | A pozzolanic reaction involves a secondary reaction whereby calcium hydroxide and usually silica ($SiO_2$) react to form the strength contributing C-S-H.<br>Due to the secondary reactions, most pozzolanic concrete develop strength beyond 28 days and up to 365 days in some cases.<br>The lower calcium hydroxide content in pozzolanic concrete leads to improved sulfate resistance. |

Table 1 (b): Extant literature on pozzolanic activity (Continued).

| Year | **Author(s)** | **Name of the paper** | **Aim of the paper** | **Parameters covered** | **Highlights and Conclusion** |
|---|---|---|---|---|---|
| 2019 | Amin, M. N., et. Al. [4] | Pozzolanic Reactivity and the Influence of Rice Husk Ash on Early-Age Autogenous Shrinkage of Concrete | Role of a rice husk ash (RHA) in reducing early-age shrinkage of high-performance concrete (HPC) after evaluating its pozzolanic reactivity. | ✓ XRD results,<br>✓ Morphology,<br>✓ Thermogravimetric Analysis,<br>✓ $Ca(OH)_2$ and CSH content. | Excellent pozzolanic potential of RHA,<br>Mitigating early-age shrinkage,<br>Burning of rice husk at controlled temperature up to 700 °C was very effective, as it has yielded silica in amorphous form,<br>Burning rice husk at high temperatures, such as 950 °C, transformed the amorphous silica into crystalline phase. |
| 2020 | Bumanis, G., et. Al. [15] | Evaluation of Industrial by-products as pozzolans: A road map for use in concrete production | Techniques adapted for evaluation of pozzolanic materials in a roadmap and do evaluation of waste stream pozzolanic materials. | ✓ XRD amorphous phase,<br>✓ XRF, $SiO_2$, $Al_2O_3$, $Fe_2O_3$,<br>✓ Alkali content,<br>✓ Particle size,<br>✓ Fineness,<br>✓ Strength Activity Index | The conflict in the effects of different aspects and chemical and physical characterization of possible pozzolans,<br>Fineness can be adjusted by proper pre-treatment such as milling,<br>The most critical aspect of pozzolanic materials tested were alkali content and their performance in cement composites, such as strength activity index and expansion due to alkali-silica reactions. |
| 2020 | Krstic, M., Rangaraju, P., & Tagnit-Hamou, A. [47] | Ground-Glass Pozzolan for Use in Concrete | Extensive research and testing have shown that several types of ground glass will perform well as a pozzolan in concrete. | ✓ Chemical Compounds,<br>✓ Alkali content,<br>✓ Sulfate Resistance,<br>✓ Chloride Permeability. | The best performance was obtained for mixtures with 30% cement replacement in chloride permeability test,<br>Cement type GUSF (general use cement containing around 8% of silica fume), |

(continued on next page)

**Table 1** (*continued*)

| Year | Author (s) | Name of the paper | Aim of the paper | Parameters covered | Highlights and Conclusion |
|---|---|---|---|---|---|
| | | | | | which has strong resistance to sulfate attack. |
| 2020 | Leussa et al., [56] | Pozzolanic activity of kaolin containing aluminum hydroxide | The study investigated the use of commercial amorphous aluminum hydroxide in addition to raw kaolinite and the use of such mixtures as supplementary cementitious materials for partial replacement of cement. | ✓ SEM images<br>✓ XRD patterns<br>✓ Setting time<br>✓ $Ca(OH)_2$ content,<br>✓ Strength Activity Index (SAI). | The incorporation of amorphous aluminum hydroxide favored the enhancement of pozzolanic activity,<br>The presence of amorphous aluminum hydroxide in clays promoted significant decrease of initial and final setting times of cement pastes,<br>The quick setting induced by amorphous aluminum hydroxide is an advantage for the elaboration of bricks or cement mortars using extrusion or vibro-compaction. |
| 2022 | Zhu, H., Chen, J., & Li, H. [100] | Effect of ultrafine pozzolanic powders on durability of fabricated hydraulic lime | Proceed to the next step, the long-term compressive strength, water absorption, water durability, and sulphate durability of the FHL prepared by the above ultrafine pozzolanic powders were investigated. | ✓ SEM results,<br>✓ XRD results,<br>✓ Water absorption,<br>✓ Compressive strength. | Nano-$SiO_2$ had a great influence on the early compressive strength and water durability of FHL paste, slag was the most important factor affecting the sulphate durability of FHL paste,<br>Based on water durability, sulphate durability and economic cost, the optimum proportion of FHL pastes was obtained as 1% nano-$SiO_2$, 2% silica fume, 10% slag, 10% fly ash, 6% CFBC ash and 69% hydrated lime. |

incorporated in concrete for the development of a greener production of construction materials. The paper aims to investigate the governing factors affecting the pozzolanic activity (fineness, $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content, calcium oxide content, and water-to-binder ratio) as well as their influence on the determination of the optimum replacement levels of such pozzolans in concrete. The concrete models determined through the carefully constructed database harvested from the recent literature along with the correlation analysis conducted using the compressive strength and strength activity index (SAI) are then utilised for the $CO_2$ emission analysis. The study is novel with its innovative threefold objectives: (1) Exploring an alternative method to produce concrete through the mechanical and durability performances concerning pozzolan incorporations; (2) Examining the influence of governing factors affecting the pozzolanic activity through the carefully constructed database using both the benchmark criteria and the correlation analysis for the attainment of the concrete models incorporating optimum replacement levels of pozzolans; (3) Conducting the $CO_2$ analysis using the concrete models on the environmental impact.

## 2. Methodology

### 2.1. Conceptual framework

The performance of pozzolans incorporated in cementitious materials have been examined using direct methods such as conventional chemical titration track $Ca(OH)_2$ presence and its gradual decline in abundance over time, and using indirect methods comprising physical and chemical analysis for the determination of pozzolanic activity and its effect on electrical conductivity, split tensile strength, and compressive strength [24]. In this study, indirect assessment methodology, based on the mechanical property evaluation; namely compressive strength and strength activity index (SAI), was adopted to gain insight into governing factors affecting the pozzolanic activity within the cementitious matrix comprehensively.

### 2.2. 2.2. Database approach and data acquisition

The database, principally constructed for the study, comprises data points harvested from 50 scientific research papers and these are summarised in Table 3. A comprehensive database comprising a total number of 631 data points harvested from the recent literature, embracing experiments conducted in the US, Canada, Europe, China, India, Turkey, and South Africa, has been compiled in Table 3. Database acquisition criteria, demonstrated in Fig. 1 comprises attainment of recent experiments, checks against norms and standards, as well as the test methods. It is then focused on the mix design principles, constitute of the materials, and the mechanical performance of cementitious materials comprising pozzolans. The database approach adopted in this paper is used for the performance and correlation analysis for the determination of the optimum concrete models comprising designated pozzolans.

### 2.3. Statistical approach, methods and tools

The database is divided into three datasets for each designated pozzolan; GGBS, fly ash and silica fume, and analyzed separately, where the critical factors, determined previously such as fineness, chemical composition (silica, alumina and iron content), water to binder ratio, as well as the calcium oxide content are investigated individually using the mechanical performance through the linear analysis. The relationship map is the constitute using the measured degree of correlations between each variables or the detection of links between elements in data analysis. This was essential to establish the correlation which enables the construction and visualization of such relations to be conducted. The Pearson correlation method is adopted to analyze the relationship between the critical factors and mechanical performance of concrete comprising GGBS, fly ash, and silica fume which represents the association between two variables. The Pearson correlation coefficients, assessing the strength of the linear link between the two variables are summarised in Table 4.

The International Business Machines Corporation (IBM) SPSS Statistics version 29.0 [40] software is utilized to extract statistics and Pearson correlations from the database. First, a 60% confidence line has been applied to each linear analysis. The results which fall out of these confidence lines are removed from the dataset. The optimized dataset is then subjected to statistics analysis to extract new Pearson correlation results. The mechanical performance of concrete is evaluated using a range of techniques. Compressive strength as well as the strength activity index (SAI) is a strategy for evaluating the mechanical performance of concrete. Strength activity index (SAI) which the ratio of the average compressive strength of test cubes that comprises pozzolans (MPa) to the average compressive strength of control cubes (MPa) is used to normalize the data by eliminating irregularities in the testing machine. ASTM C618–22, Standard Specification for Coal Fly Ash and

**Table 2**
Summary of recent life cycle analyses of various pozzolanic materials.

| Year | Author (s) | Software | Methodology & Impact Categories | Materials | Highest Impact | Lowest Impact | Output |
|---|---|---|---|---|---|---|---|
| **2015** | Crossin [21] | SimaPro 7.2.4 | ISO 14044:2006 | • GGBFS<br>• OPC | OPC | GGBFS | • The use of GGBFS as a cement replacement in concrete can reduce greenhouse gas emissions by 47.5%. |
| **2016** | Gursel et al., [34] | The GreenConcrete | Not Specified. | • OPC<br>• Fly Ash<br>• Rice Husk Ash | OPC | Fly Ash | • Utilizing locally accessible SCMs should be one of many actions made to reduce the problems brought on by excessive PC utilization and significantly reduce the carbon footprint of the concrete. |
| **2017** | Van den Heede & De Belie [92] | SimaPro 8 | CML-IA | • Fly Ash<br>• Silica Fume<br>• BFS<br>• OPC | OPC | GGBS | • All examined concrete compositions with fly ash (and silica fume) or BFS are more sustainable than the reference concrete in terms of all ten CML-IA baseline impact metrics.<br>• Economic allocation is believed to have a balanced influence on byproducts. However, this is not always the case because their availability and consequent pricing differ from nation to country. |
| **2018** | Hossain et al., [38] | SimaPro 8.1.5 | IMPACT 2002 + | • OPC<br>• Silica Fume<br>• Fly Ash<br>• GBFS | OPC | SCMs | • Most of the research that were analyzed ignored mass allocation since it has significant negative environmental effects.<br>• SCMs were shown to have a 20–38% lower global warming potential than OPC concrete. |
| **2020** | Arrigoni et al., [5] | Not Specified. | ISO 14040 & 14044 | • OPC<br>• Fly Ash<br>• GGBS<br>• Volcanic Ash<br>• Oil Shale Ash<br>• RHA<br>• MK<br>• Ground Bottom Ash<br>• GCCR<br>• Silica Fume | OPC And GGBS+SF | GBA+GCCR | • Because their usage may need modifications to the mix or extensive transport distances, not all SCMs guarantee fewer emissions.<br>• "The more SCM utilized, the better for GHG" is not always true because the largest substitution of PC by SCM did not always result in the lowest GHG. |
| **2021** | Manjunatha et al., [60] | SimaPro8.1 | The ReCiPe 2016 | • OPC<br>• GGBS<br>• PPC | OPC | GGBS, Fly Ash | • GGBS and PPC decrease the overall climate change impacts. |
| **2021** | Radwan et al., [77] | SimaPro | The ReCiPe 2016 | • OPC<br>• GGBS<br>• Fly Ash | OPC | Fly Ash | • OPC-GGBS-Fly ash ternary blended systems are suggested for producing eco-friendly concrete.<br>• The best GWP/Strength Ratio is achieved in 10–20% of Fly Ash incorporation. |
| **2022** | Fallah-Valukolaee et al., [26] | SimaPro8.1 | BEES | • OPC<br>• Silica Fume<br>• Nano Silica | Silica Fume | OPC | • Control has the greatest impact on Climate Change; however, Silica Fume replacement delivers the highest impacts on other categories. |
| **2022** | Pradhan et al., [74] | SimaPro9.1 | CML 2 baseline 2000 V2.05 | • OPC<br>• Fly Ash<br>• GGBS<br>• LC | OPC | LC | • The GWP of Fly Ash (30%), GGBS (50%), and Limestone Calcined Clay mixtures is reduced by 23%, 34%, and 44%, respectively, when compared to the control mix. |

Raw or Calcined Natural Pozzolan for Use in Concrete and ASTM C595–21 Standard Specification for Blended Hydraulic Cements have been reviewed to determine the acceptable benchmark in Strength Activity Index. ASTM C618 and ASTM C595 suggest that blended concrete has to deliver a minimum of 75% strength activity index at 7 and 28 days, are summarized in Table 5.

Although most of the concrete samples exposed to compressive strength were cubes, cylinder concrete samples have then been converted to the cube sampling in the database. Conversion factors from cylinder to cubes for concrete specimens reported in the literature often ranges from 0.77 to 0.96 [79,85,87]. Compressive strength values of cylinder specimens are converted to cube specimens by a conversion factor of 0.80.

$CO_2$ emissions of the designated pozzolans incorporated in concrete at varying replacement levels were used to estimate the environmental impact of each material through the $CO_2$ emission factors provided in Table 6. According to Portland Cement Association (2023) [89], each kg of Ordinary Portland Cement emits 0.9 kg of carbon dioxide into the atmosphere during the whole manufacturing process of the binder. Flower and Sanjayan, [28] indicates that the $CO_2$ emission coefficients of fine and coarse aggregates are 0.0139 kg $CO_2$/kg, and 0.0459 kg $CO_2$/kg, respectively. Emission factors of pozzolans range from 0.026 to 0.143 for GGBS (Kavitha, 2017); [28], 0.004–0.027 for fly ash [28], and 0.028 for silica fume [50]. The emission coefficients, summarised in Table 6, comprises extracting, cutting, grinding, screening, and transportation impacts on emission scores.

## 3. Data analysis and results

### 3.1. Raw data

This section aims to demonstrate the regular scatter attained through the raw data harvested from the recent literature with regards to determining the optimum replacement levels of pozzolans incorporated in concrete. It is worth nothing that highest number of data points is attain on GGBS incorporated in concrete with 313 no. of data points, whereas fly ash and silica fume have 115 and 112 no. of data points in the database. Although the GGBS incorporation in concrete ranged from 5% to 80%, this range varied from 5% to 70% for fly ash, and 3–30% for silica fume. Fig. 2a demonstrate the degree of the scatter attain when

**Table 3**
Summary of the database undertaken in the present study.

| # | Year | Author (s) | Country | Pozzolan (s) | # of Data |
|---|---|---|---|---|---|
| 1 | 2022 | Liu et al., [58] | Japan | Fly Ash, GGBS | 13 |
| 2 | 2010 | Nochaiya et al., [70] | Thailand | Fly Ash, Silica Fume | 7 |
| 3 | 2008 | Yazıcı [96] | Türkiye | Silica Fume, Fly Ash | 9 |
| 4 | 2020 | Qureshi et al., [76] | Pakistan | Silica fume, GGBS, fly ash | 5 |
| 5 | 2021 | Biswal & Dinakar [11] | India | Fly Ash, GGBS | 18 |
| 6 | 2014 | Rashad et al., [78] | Egypt | GGBS, Fly Ash, Silica Fume | 8 |
| 7 | 2015 | Kumar Karri et al., [54] | India | GGBS | 8 |
| 8 | 2015 | Venkatakrishnaiah [93] | India | GGBS, Fly Ash, Silica Fume | 3 |
| 9 | 2018 | Mohamed [64] | UAE | GGBS, Fly Ash, Silica Fume | 26 |
| 10 | 2021 | Prakash et al., [75] | India | Silica Fume, GGBS | 17 |
| 11 | 2022 | Tadi & Rao [86] | India | GGBS | 7 |
| 12 | 2016 | Reddy et al., [94] | India | Micro Silica, GGBS | 13 |
| 13 | 2011 | Megat Johari et al., [62] | Malaysia | GGBS, Fly Ash, Silica Fume | 13 |
| 14 | 2021 | Kumar et al., [51] | Pakistan | Fly Ash, Silica Fume | 10 |
| 15 | 2007 | Oner & Akyuz [71] | Türkiye | GGBS | 32 |
| 16 | 2020 | Suda & Rao [84] | India | Micro Silica, GGBS | 13 |
| 17 | 2017 | Joshaghani et al., [43] | USA | GGBS, Fly Ash, Silica Fume | 10 |
| 18 | 2001 | Poon et al., [73] | China | GGBS, Fly Ash, Silica Fume | 14 |
| 19 | 2019 | Phul et al., [72] | Pakistan | GGBS, Fly Ash | 10 |
| 20 | 2019 | Mohamed & Najm [65] | UAE | Fly Ash, Micro Silica, GGBS | 20 |
| 21 | 2018 | Mohan & Mini [68] | India | GGBS, Silica Fume | 7 |
| 22 | 2019 | O. A. Mohamed [66] | UAE | Fly Ash, Micro Silica, GGBS | 15 |
| 23 | 2008 | Chidiac & Panesar [19] | Canada | GGBS | 13 |
| 24 | 2009 | Shi et al., [81] | China | GGBS, Fly Ash | 19 |
| 25 | 2022 | Hatami & Amiri [37] | Iran | GGBS | 45 |
| 26 | 2021 | Tangadagi et al., [88] | India | GGBS | 9 |
| 27 | 2022 | Bulut & Şahin [14] | Türkiye | GGBS, Fly Ash, Silica Fume | 10 |
| 28 | 2017 | Hussain et al., [39] | India | Fly Ash | 6 |
| 29 | 2013 | Dinakar et al., [22] | India | GGBS | 8 |
| 30 | 2022 | Singh et al., [83] | India | Silica Fume, Fly Ash | 20 |
| 31 | 2022 | M. H. Kumar et al., [52] | India | Fly Ash, Silica Fume | 12 |
| 32 | 2012 | Boukendakdji et al., [13] | Algeria | GGBS | 3 |
| 33 | 2022 | Gilayeneh et al., [30] | South Africa | GGBS, Fly Ash, Silica Fume | 5 |
| 34 | 2022 | S. Kumar et al., [53] | India | Fly Ash, Silica Fume | 10 |
| 35 | 2017 | Moffatt et al., [63] | Canada | Fly Ash | 13 |
| 36 | 2013 | Dinakar et al., [23] | India | Fly Ash | 4 |
| 37 | 2019 | Nadiger & Madhavan [69] | India | Silica Fume | 27 |
| 38 | 2016 | Gupta [33] | India | GGBS | 7 |
| 39 | 2007 | Güneyisi & Gesoğlu [31] | Türkiye | GGBS | 5 |
| 40 | 2007 | Gesoğlu & Özbay [29] | Türkiye | GGBS, Fly Ash, Silica Fume | 22 |
| 41 | 2018 | Coppola et al., [20] | Italy | Fly Ash, Ultrafine Fly Ash | 11 |
| 42 | 2021 | Zhang et al., [99] | China | GGBS, Fly Ash, Silica Fume | 17 |
| 43 | 2004 | Toutanji et al., [91] | USA | GGBS, Fly Ash, Silica Fume | 16 |
| 44 | 2018 | Bin Muhit [10] | Korea | GGBS, Fly Ash, Silica Fume | 17 |
| 45 | 2008 | Chen & Liu [17] | China | GGBS, Fly Ash, Silica Fume | 16 |
| 46 | 2012 | Güneyisi et al., [32] | Türkiye | Fly Ash, Silica Fume | 9 |
| 47 | 2018 | H. J. Chen et al., [18] | Taiwan | GGBS, Fly Ash | 8 |
| 48 | 2011 | Akçaözoğlu & Atiş [3] | Türkiye | GGBS, Fly Ash | 6 |
| 49 | 2003 | Kılıç et al., [49] | Türkiye | Silica Fume, Fly Ash | 6 |
| 50 | 2004 | Lo et al., [59] | Hong Kong | Fly Ash | 9 |

*GGBS, fly ash, and silica fume combinations are included. Total # of Data points 631 *

compressive strength is plotted versus the replacement levels of pozzolans incorporated in concrete. It is clearly shown in Fig. 2a that it is impracticable to determine the optimum replacement levels of GGBS, fly ash and silica fume due to the high degree of noise attain in the data distribution.

Compressive strength of concrete incorporated various replacement levels of GGBS, a pozzolanic substitution, has been particularly shown in Fig. 2b to demonstrate the degree of scatter attain and the impracticability of attaining the optimum replacement levels of such substitutions in concrete through this sole approach. The scatter demonstrated in Fig. 2b is mainly due to the variations attained in mix design such as the use of varying binder type, varying water content, varying amounts and fractions of fine & coarse aggregate, the use of additives or plasticisers and hence the scatter is essentially expected. Fig. 2b indicates that the increase in the replacement levels of GGBS yields in a gradual reduction on the compressive strength of concrete. This would have been a controversial finding if the plot has been designed with respect to the optimum replacement level of GGBS. Silica of the pozzolans react with calcium hydroxide and forms additional calcium-silicate-hydrate gels that improve the strength of such matrix particularly at long-term. It is apparent that researchers conducted higher replacement levels of pozzolans to gain insight in to the concrete properties with high replacement levels of pozzolans but this has resulted in a reduction in compressive strength possibly because of the insufficient amount of calcium silicate left in the material for the pozzolanic reaction. It should however be noted that American Concrete Institute, 2019 [1] code requires a minimum specified compressive strength of 35 MPa. This barrier is shown with a dashed line in Fig. 2b and that the most of the values satisfy the benchmark for construction purpose concrete compressive strength. The sound methodology to determine the optimum replacement level of pozzolans incorporated in concrete comprises the influence of the governing factors affecting the pozzolanic activity; fineness, amorphousness, water-to-binder ratio, silica-alumina-iron and calcium oxide content.

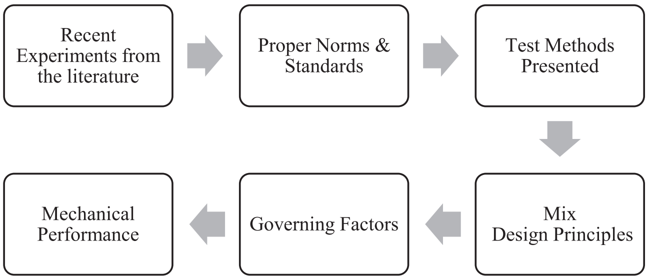


**Fig. 1.** Database acquisition criteria step by step.

### 3.2. Factors

This section investigates the influence of the governing factors on compressive strength of concrete incorporating pozzolans such as GGBS, fly ash, and silica fume which is aiming to compile the database for the determination of the optimum replacement levels.

#### 3.2.1. Fineness

This section investigates the influence of fineness on the compressive strength of concrete comprising GGBS as a pozzolanic substitute. Fig. 3a shows that the fineness interval of GGBS ranges from 350 $m^2/kg$ to 600 $m^2/kg$, and its replacement levels varies from 5% to 80%. It should also be noted that Fig. 3a comprises the data points attained from the database as raw results. It is shown in Fig. 3a that the increase in the fineness yields to an increase in the compressive strength of concrete incorporating varying replacement levels of GGBS. It should also be noted that the Pearson's correlation between the fineness and compressive strength of concrete is 0.447 and hence reveals strong positive relationship between these properties.

Following numerous intertrials conducted by the authors, it was observed that 60% confidence intervals capture most of the data points representing compressive strength of concrete incorporating GGBS and hence 60% confidence interval lines were designated to be the approach adopted for the dataset herein. Following 60% confidence interval is applied to best fit line of fineness in Fig. 3a, the data points that fall out of these interval lines are then removed from the dataset and fineness versus the compressive strength of concrete incorporating GGBS is re-plotted in Fig. 3b. The increase in compressive strength with the increase in fineness became more distinct following the utilisation of the confidence intervals in Fig. 3b and hence reassured the strong relationship between the fineness of pozzolans and compressive strength. It is a well-known fact that the compressive strength below 20 MPa is not considered to be a structural concrete in practise. Also, the compressive strength above 100 MPa is often is impractical to attain in construction industry. The fineness above 500 $m^2/kg$ often results in a significant additional water demand in the mixture to attain the required consistence at the plastic phase which yields to a substantial reduction on the compressive strength of concrete at hardened stage. Based on these scientific barriers, the optimum replacement level of GGBS, concerning the influence of fineness on the pozzolanic activity, is determined to be in the range of 25–50% and is demonstrated in Fig. 3b.

Furthermore, Fig. 3c demonstrates the influence of fineness on the strength activity index of concrete incorporating GGBS. The strength activity index ranges from 60% to 160%, while the replacement levels ranged from 5% to 80%. It is clearly demonstrated in Fig. 3c once again that the increase in the fineness of GGBS significantly increased the compressive strength of concrete mainly as a result of the matrix densification. The optimal replacement level of GGBS based on the strength activity index is determined to be in the range of 40–55%. Previously, the GGBS optimal replacement levels were determined to be in the range of 25–50% with respect to compressive strength evaluations and hence the replacement levels of 40–55% with respect to strength activity index falls well within this range which provides re-validation of the governing influence of the fineness as well as the confirmation of the substation level of GGBS in concrete. The results demonstrated in Fig. 3a–c) are in line with the previously reported findings and hence it is widely documented that the responsible mechanism for the increase in compressive strength is the finer characteristics of GGBS which has a filler effect in the cementitious matrix, enabling significant densification of the microstructure, therefore leading to substantial enhancement in the mechanical properties of concrete incorporating GGBS [15,48,61,67,100].

Fig. 3d demonstrate the optimal replacement level attainment of concrete incorporating fly ash using the similar principles described for GGBS in the previous Figures (a-c). It is evidently shown in Fig. 3d that the increase in the fineness again results in the increase in compressive strength of concrete incorporating fly ash where the fineness interval of the fly ash ranged from 250 $m^2/kg$ to 680 $m^2/kg$, and its replacement interval from 5% to 70%. Following a 60% confidence interval was applied, the fineness interval was confined to 300 $m^2/kg$ to 420 $m^2/kg$, whereas the replacement ranges from 10% to 60%. The optimal replacement level of fly ash in concrete therefore is determined to be in the range of 10–30% and is shown in Fig. 3d. The similar principles were also utilised for the determination of the optimal replacement level of silica fume and were detected to be in the range of 5–15% which is summarised in Table 8(b) later.

**Table 4**
Pearson Correlations [25].

| Coefficient Range | Correlation Descriptions |
|---|---|
| 0.70 or higher | Very strong relationship |
| 0.40–0.69 | Strong relationship |
| 0.30–0.39 | Moderate relationship |
| 0.20–0.29 | Weak relationship |
| 0.01–0.19 | No or negligible relationship |
| 0 | No relationship [zero correlation] |

**Table 5**
Strength Activity Index Requirements of ASTM C618–22 and C595–21.

| Standards | Types of Blended Cement | Strength Activity Index (SAI) |
|---|---|---|
| ASTM C595 (2021) [7] | a. Portland Blast-furnace slag cement.<br>b. Portland-Pozzolan cement.<br>c. Ternary blended cement.<br>d. Portland-Limestone cement | 75% |
| ASTM C618 (2022) [6] | e. Portland-Coal Fly Ash (N/F/C Type) cement | |

**Table 6**
$CO_2$ Emission Factors.

| Materials | $CO_2$ Emission Factors (kg $CO_2$/kg) |
|---|---|
| Ordinary Portland Cement | 0.9 (PCA, 2023) [89] |
| Fine Aggregates | 0.0139[28] |
| Coarse Aggregates | 0.0459[28] |
| GGBS | 0.026–0.143 (Kavitha, 2017)[28] |
| Fly Ash | 0.004–0.027[28] |
| Silica Fume | 0.028[50] |

#### 3.2.2. Mineralogy

The influence of the chemical composition of pozzolans on the compressive strength of concrete is investigated in this section. Fig. 4a demonstrates the compressive strength of concrete incorporating the designated pozzolans versus the $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content of these materials. It can be detected from the figure that the $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ contents of GGBS is in the range of 45–55%, whereas this range is between 75% and 95% for fly ash, and 85–100% for silica fume. It is shown in Fig. 4a that the increase in the content of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ results in a significant increase in the compressive strength of

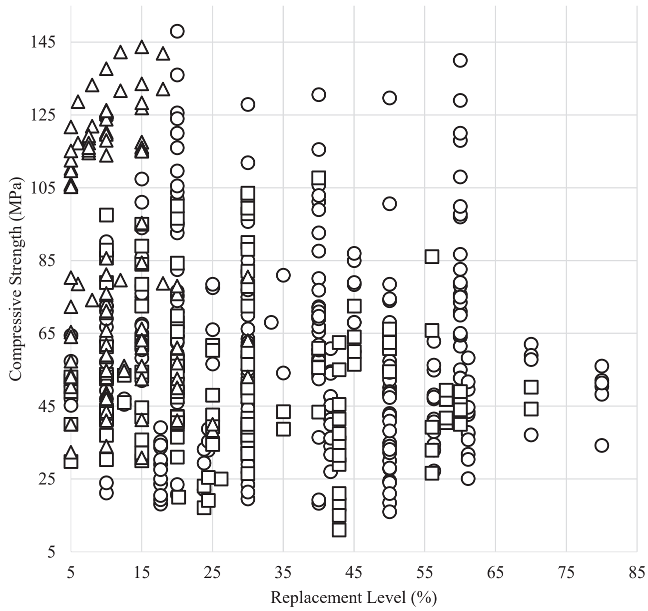


**Fig. 2a.** Compressive strength of concrete comprising varying replacement levels of pozzolans; ○, GGBS; □, fly ash; Δ, silica fume.

concrete incorporating fly ash and silica fume.

According to ASTM C618 (2022), the sum of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content of a pozzolan must be minimum 70% which is reported to be essential for the pozzolanic reaction. Fig. 4a shows a steady decrease in the compressive strength of concrete incorporating GGBS with the increase in $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content. Although the results exhibit a controversial circumstance, the decrease attained in compressive strength is possibly due to the high burning temperatures utilised in the production process of GGBS which conceivably resulted in the diminishing of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content and consequently formed higher amounts of calcium oxide (CaO) compared to the other designated pozzolans studied herein. It must be reported that the calcium oxide content of GGBS is in the range of 30–45% whereas this range is up to 10% for fly ash and up to 3% for silica fume.

$SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content versus the compressive strength of

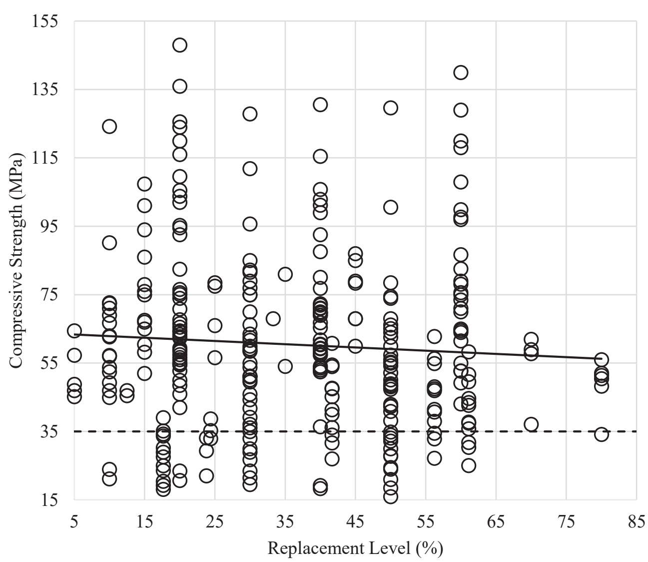


**Fig. 2b.** Compressive strength of concrete comprising varying replacement levels of GGBS. The trend solid line represents the best fit for compressive strength of concrete incorporating GGBS. The dashed line represents the minimum specified compressive strength of concrete by ACI 318–19.

concrete incorporating fly ash is shown in Fig. 4b. Fly ash is selected herein purposely to represent a pozzolan with a high content of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$. Fig. 4b shows that the increase in the $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content resulted in significant increase ın the compressive strength of concrete incorporating fly ash. It must be noted that strength values shown in Fig. 4b range from 20 MPa to 100 MPa, most of which is relatively high to attain in practice. The increase attained in the replacement level of fly ash on the other hand resulted in a steady decrease in the compressive strength of concrete. The decrease attained in compressive strength often results due to the fact that there might be insufficient amount of calcium hydroxide in the matrix to bound the silica of the pozzolans and hence this may result in the diminishing of strength. The dashed line in Fig. 4b, represents the best fit line for concrete incorporating varying replacement levels of fly ash and that the findings reported here indicate that the optimum replacement ranges for fly ash can be considered to be in the range of 25–35%. The similar principles were also utilised for the determination of the optimum replacement level of silica fume and were detected to be in the range of 5–15% which is summarised in Table 8(b) later.

### 3.2.3. *Water-Binder Ratio*

Water is essential within the cementitious media mainly for two vital reasons; for the required consistence to be attained at the plastic stage and for the hydration reaction for the development of strength. Fig. 5a shows the water:binder ratio versus the compressive strength of concrete incorporating GGBS. It is shown in Fig. 5a that the highest compressive strength of concrete incorporating GGBS is attained when water:binder ratio is in the range of 0.20–0.45. This ratio ranges from 0.20 to 0.40 for fly ash and 0.15–0.30 for silica fume (later summarised in Table 8b). It is well documented in the literature that there is a very critical stability exist between the consistence and the hydration reactions when it comes to determine the required water content for a particular mix. This is mainly because the amount of water that is essential to attain consistence is usually higher than the water required for the hydration reaction for the strength development. The increase in the water content to satisfy the consistence at the plastic stage often yields to a substantial reduction in strength as the excess water leaves the matrix and generates undesirable pore development. However, the use of insufficient amount of water also results in a poor strength development due to the inadequate amount of water that leads to incomplete hydration reactions.

The increase in the replacement level of GGBS, particularly from 35% onwards, usually yields to reduction in the compressive strength. This is expected principally at the short-term; as the very hydraulic binder cement is being replaced with a pozzolanic material which not only depending on the development of the hydration reaction and therefore the formation of calcium hydroxide for the pozzolanic reaction but also has a much slower nature than that of the cement hydration. The optimum replacement of GGBS concerning water:binder ratio can be determined to be in the range of 15–35%. The similar principles were also utilised for the determination of the optimum replacement level of silica fume and fly ash and were detected to be in the range of 5–15% and 15–30% respectively and are summarised in Table 8(b) later.

Fig. 5b has been constructed in purpose to demonstrate the long-term influence of GGBS on the compressive strength of concrete. The figure consists of data points representing compressive strength of concrete specimens that are at least 180 days old. It is evidently shown in the Fig. 5b that the increase in the replacement level of GGBS resulted in a substantial increase in the compressive strength of concrete at the long-term. The time for the pozzolanic reaction is required as the calcium hydroxide forms as a result of the hydration reaction which is then used to react with silica available in the matrix. The higher strength attained at long-term is as a result of the transformation of most of the calcium hydroxide to calcium-silicate-hydrate gels that are responsible from the strength development of the matrix.

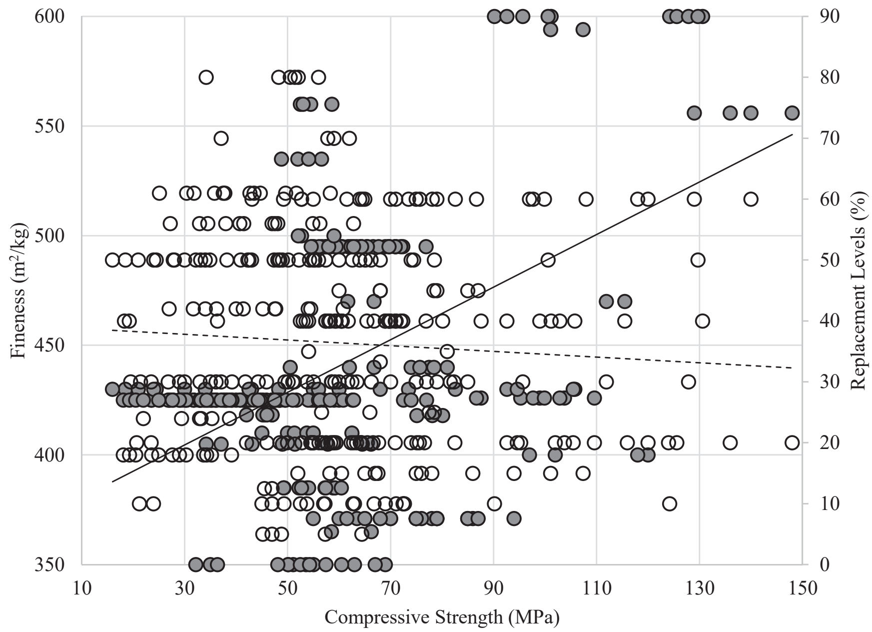


**Fig. 3a.** Fineness versus the compressive strength of concrete incorporating GGBS, •; fineness, ○; replacement level. (Secondary axis display the replacement levels of GGBS). Solid line represents the best fit for fineness and the dashed line represents the best fit for replacement levels.

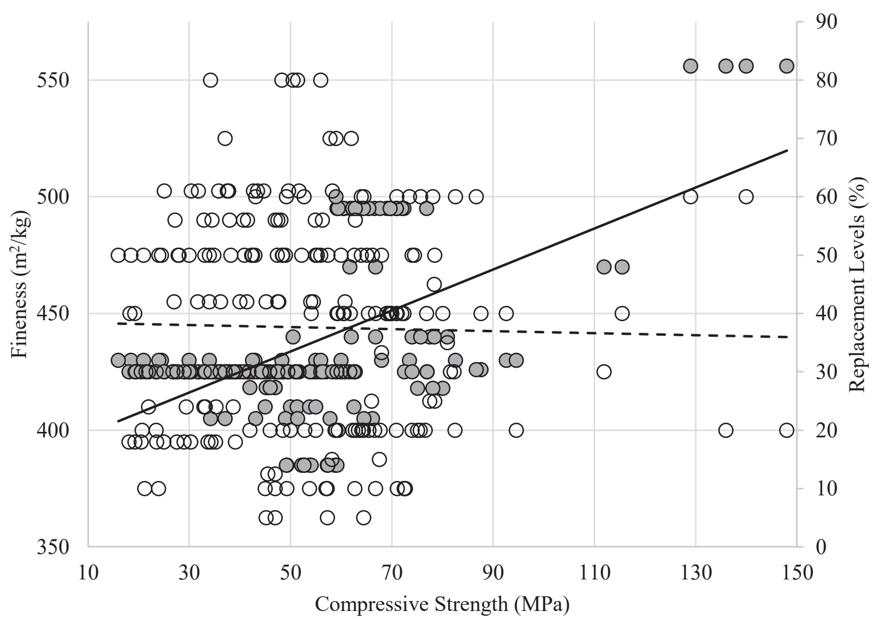


**Fig. 3b.** Fineness versus the compressive strength of concrete incorporating GGBS using the optimised GGBS dataset, •; fineness, ○; replacement level. (Secondary axis display the replacement levels of GGBS). Solid line represents the best fit for fineness and the dashed line represents the best fit for replacement levels.

*3.2.4. Calcium oxide content*

The calcium hydroxide content of GGBS, fly ash and silica fume, incorporated in concrete in this study, are shown in Fig. 6a. The figure demonstrates that GGBS has much higher calcium oxide (CaO) content with 30–45% compared to that of fly ash (up to 7%) and silica fume (up to 3%). It is evidently shown in Fig. 6a that increase in the calcium oxide content has a positive effect on the compressive strength of concrete incorporating GGBS. On the other hand, the increase in the CaO content results in a decrease in the compressive strength of concrete comprising fly ash and silica fume. It is reported in the literature that the CaO content does not only enhance the calcium source of the matrix but also contributes in the rise of temperature as a result of the exothermic reaction between water and CaO [55]. This feature of CaO enables more consolidated matrix with improved mechanical properties as a result of the accelerated reactions taking place at the plastic stage [44]. The improved durability characteristic of cementitious materials comprised high CaO content of pozzolans are well reported in Lee and Lee (2020) and Ju et al., [44]. It is also reported in the literature that the free CaO enhances the pozzolanic reaction and that higher amount of calcium-silicate-hydrated gels are produced by cementitious materials comprising pozzolans with greater CaO contents which yields to a greater strength development of these materials [82].

Fig. 6b shows the calcium oxide content of GGBS plotted versus the compressive strength of concrete comprising GGSB. The secondary axis represents the replacement levels of such pozzolanic substitute. The steady increase in concrete compressive strength with the increase in

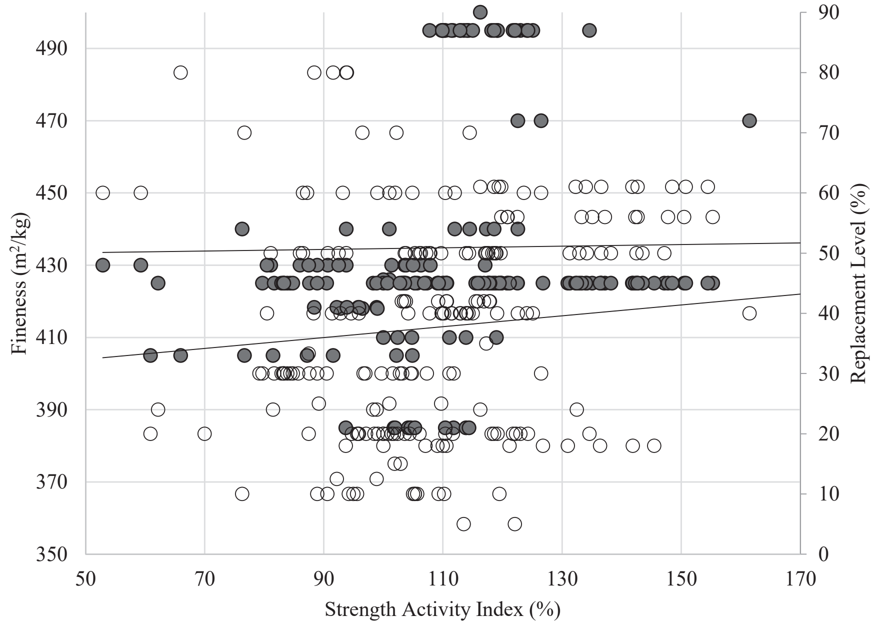


**Fig. 3c.** Fineness versus the strength activity index of concrete incorporating GGBS using the optimised GGBS dataset, •; fineness, ○; replacement level. (Secondary axis display the replacement levels of GGBS). Solid line represents the best fit for fineness and the dashed line represents the best fit for replacement levels.

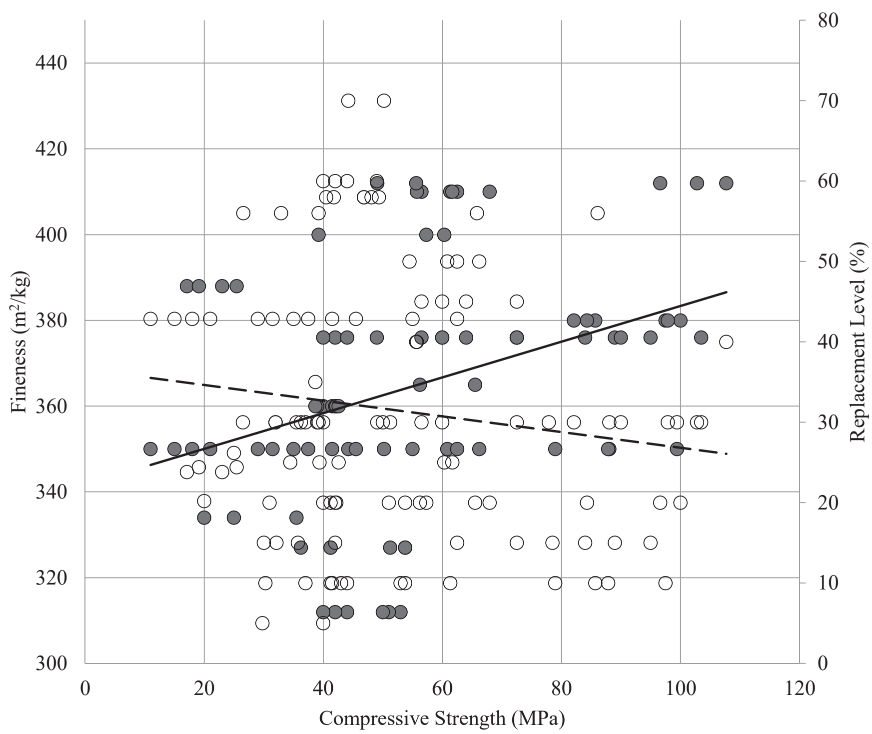


**Fig. 3d.** Fineness versus the compressive strength of concrete incorporating fly ash using the optimised fly ash dataset, •; fineness, ○; replacement level. (Secondary axis display the replacement levels of fly ash). Solid line represents the best fit for fineness and the dashed line represents the best fit for replacement levels.

CaO content of GGBS is evidently shown in Fig. 6b. Although the increase in the replacement levels of GGBS increases the compressive strength of concrete, this relationship ceased when the replacement level reaches to 40%. Therefore, the optimum replacement level of GGBS comprising high content of CaO is determined to be in the range of 30–40%. Although the calcium oxide content alone does not seem to have a positive influence on the strength development of concrete, following the 60% confidence interval approach is conducted the optimum replacement level of fly ash and silica fume are determined to be in the range of 10–30% and 7.5–15% respectively.

### 3.3. Statistical analysis

#### 3.3.1. Descriptive statistics

Table 7(a) - (c) summarise the basic statistics of the datasets attained for replacement level (%), compressive strength (MPa), fineness ($m^2$/kg), $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content (%), calcium oxide content (%) and water: binder ratio for the designated pozzolans, GGBS, fly ash and silica

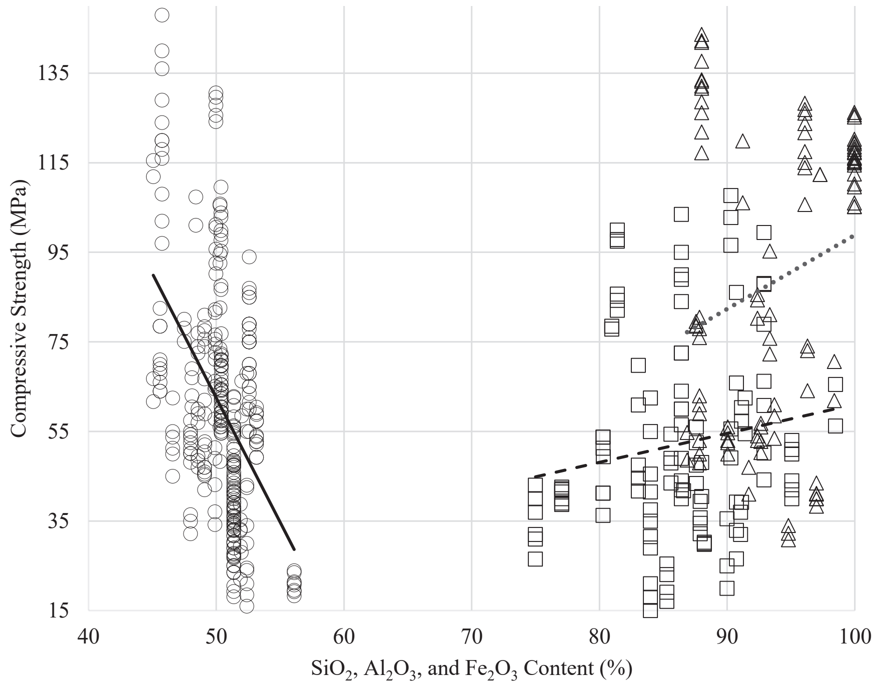


**Fig. 4a.** Compressive strength of concrete incorporating the designated pozzolans versus the $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content; ○, GGBS; □, fly ash; Δ, silica fume. Solid line, dotted line and the dashed line represent the best fit for GGBS, silica fume and fly ash respectively.

fume respectively. The data comprises the minimum, maximum, and mean values of each parameter considered. Typical fineness intervals are in the range of 350 $m^2/kg$ to 750 $m^2/kg$ for GGBS, 250 $m^2/kg$ to 680 $m^2/kg$ for fly ash, and 1800 $m^2/kg$ to 30000 $m^2/kg$ for silica fume. Concrete incorporating GGBS produces16MPa to 148 MPa compressive strength, whereas fly ash and silica fume yield 11–107 MPa and 30–143 MPa, respectively. Descriptive statistics such as the mean and standard deviation of concrete comprising the designated pozzolans are summarised in Table 7(a), (b) and (c). The average replacement levels of GGBS, fly ash, and silica fume in concrete were found to be 36%, 29%, and 11%, respectively. GGBS comprises the lowest content of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content whereas has the highest content of Calcium Oxide. The mean value of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ contents of fly ash and silica fume incorporated in concrete are 86% and 94%, respectively. It is also summarised in Table 7(b) and (c) that fly ash and silica fume incorporated in concrete are rich in $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content compared to that of the GGBS.

### 3.3.2. *Correlation analysis*

Pearson correlations, applied to the raw data as well as on the

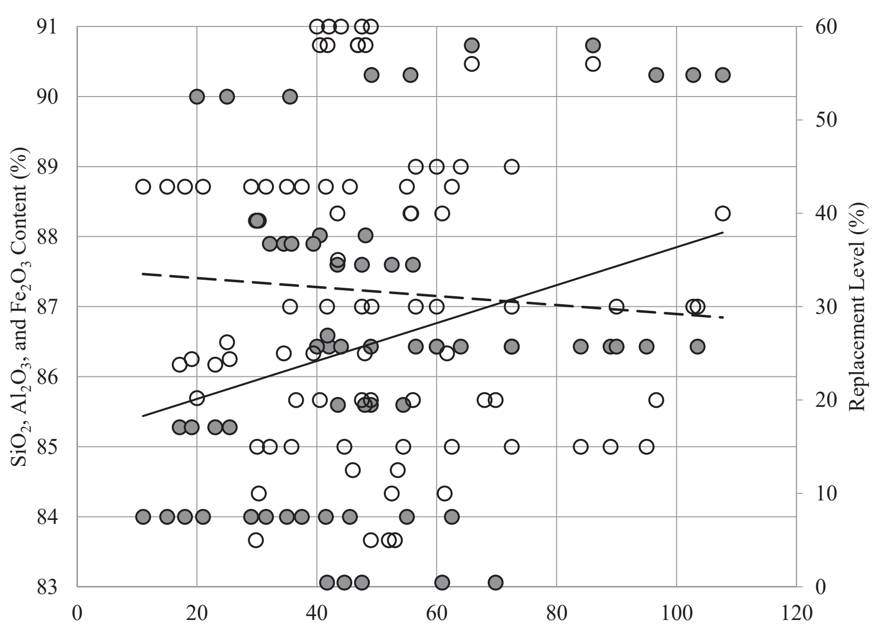


**Fig. 4b.** $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content versus the compressive strength of concrete incorporating fly ash, the optimised data. ●, $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content; ○, replacement levels of fly ash. Solid line represents the best fit for $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content and the dashed line represents the best fit for replacement levels.

optimized data, attained using the evaluations explained in Section 3.2 previously, are summarised in Table 8(a). The Pearson correlations of compressive strength of concrete incorporating the designated pozzolans using the governing factors affecting the pozzolanic activity such as $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content, fineness ($m^2$/kg), $SiO_2$, water: binder ratio and calcium oxide content (%) are summarised in Table 8(a). It is evidently demonstrated in Table 8(a) that the Pearson correlation factors have substantially increased when the raw data is refined and optimised data is attain using the principles previously explained in Section 3.2. The increase attained in the Pearson correlations have demonstrated the achievement towards the positive strong relationship of the governing factors on the compressive strength of concrete incorporating the designated pozzolans. For instance, the Pearson correlation coefficient of calcium oxide content of GGBS is increased from 0.204 to 0.634 when the data is optimised. This is a clear indication of the strong positive relationship of calcium oxide on the strength development of concrete incorporating high content of CaO. The water:binder ratio of all pozzolans demonstrated a considerable increase in the Pearson correlations when the optimised data is utilised and once again re-validated the very strong positive relationship of this governing factor on the compressive strength of concrete incorporating pozzolans. Similarly, the Pearson correlation coefficient of fineness exhibited a considerable increase when optimised data is used and again re-validated the significance of this factor on the strength development of such materials. Although a substantial increase in the Pearson correlations are attained when using the optimised data for $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content, the lesser increase attained in fly ash incorporation for instance is in line with the lesser attainment of compressive strength of concrete incorporating fly ash as previously demonstrated in Fig. 4a. The GGBS and silica fume incorporation in concrete resulted in a very strong and strong positive relationship attainment respectively when using the optimised data. The results summarised in Table 8(a) give confidence in re-validating the significant influence of the governing factors on the strength development of concrete comprising the designated pozzolans and hence re-build an assurance that the optimum replacement levels previously determined using the database approach. Based on both the performance analysis performed in Section 3.2 as well as the correlation analysis conducted in this section the optimum replacement levels of designated pozzolans to be incorporated in concrete were determined and are summarised in Table 8(b). The optimum replacement level of GGBS is determined to be in the range of 15–50% whereas this ratio is ranged from 10% to 35% for fly and 5–15% for silica fume.

| Pozzolan | | $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content (%) | Fineness ($m^2$/kg) | Water: binder ratio | Calcium Oxide content (%) |
|---|---|---|---|---|---|
| GGBS | Optimal Replacement Intervals | 35–45% | 25–50% | 15–35% | 30–40% |
| | **Min/Max** | **15–50%** | | | |
| FLY ASH | Optimal Replacement Intervals | 25–35% | 10–30% | 15–30% | 10–30% |
| | **Min/Max** | **10–35%** | | | |
| SILICA FUME | Optimal Replacement Intervals | 5–10% | 5–15% | 5–15% | 5–15% |
| | **Min/Max** | **5–15%** | | | |

### 3.4. Optimum concrete models

The optimum replacement levels of designated pozzolans, meticulously determined in Sections 3.2 and 3.3, incorporated in concrete models are studied here. The optimum replacement ranges for each designated pozzolan is used to assign the minimum and maximum replacement levels of each substitute in Table 9. Therefore, the concrete models comprising optimum replacement levels of each designated pozzolan have been reflected into Table 9. The GGBS incorporation in concrete for instance has been shown to have 15% as the minimum and 50% as the maximum substation level for this specific replacement. It is essential to note that the mix constituents such as the amount of pozzolans, binder, fine and course aggregates have been determined based on the mean of the representing data sets for this specific model. The determination of mix constituents, summarised for each concrete model incorporating the optimum replacement levels of the designated pozzolans, were essential so that the sustainability assessment of such models through the carbon emission factors can be performed. It should also be noted that the control model has been generated from the dataset comprising just the plain concrete with no pozzolanic replacements. Once again, the average, the mean values for each mix constituent have

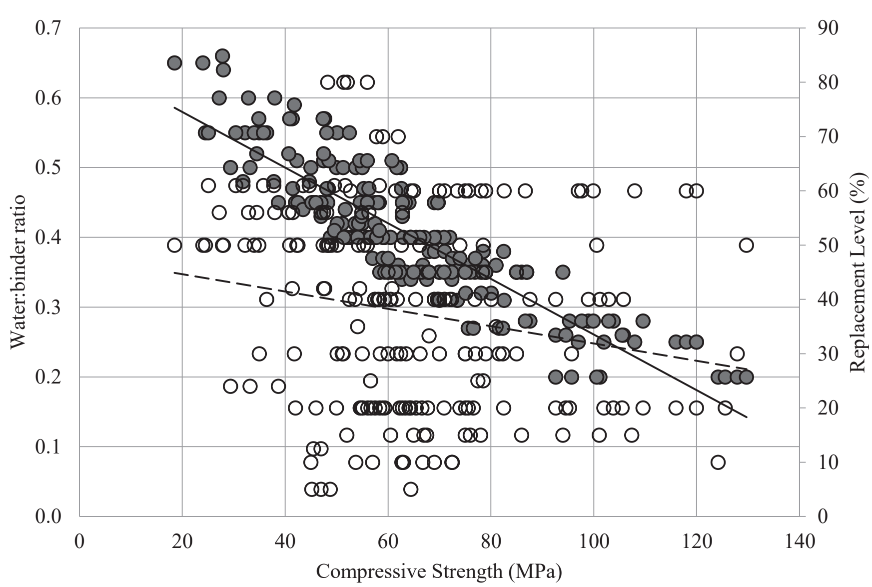


**Fig. 5a.** Water-binder ratio versus compressive strength of concrete incorporating GGBS, Optimized GGBS Data. (Secondary axis represents the replacement levels of GGBS) •, water:binder ratio; ○, replacement levels of GGBS. Solid line represents the best fit for water:binder ratio and the dashed line represents the best fit for replacement levels.

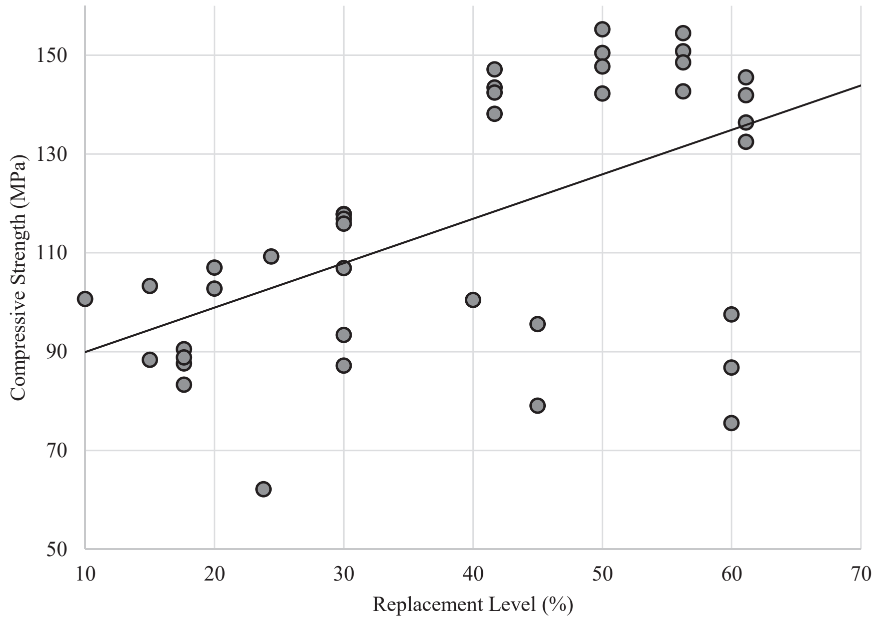


**Fig. 5b.** Compressive strength versus replacement levels of concrete incorporating GGBS aged 180 days and older.

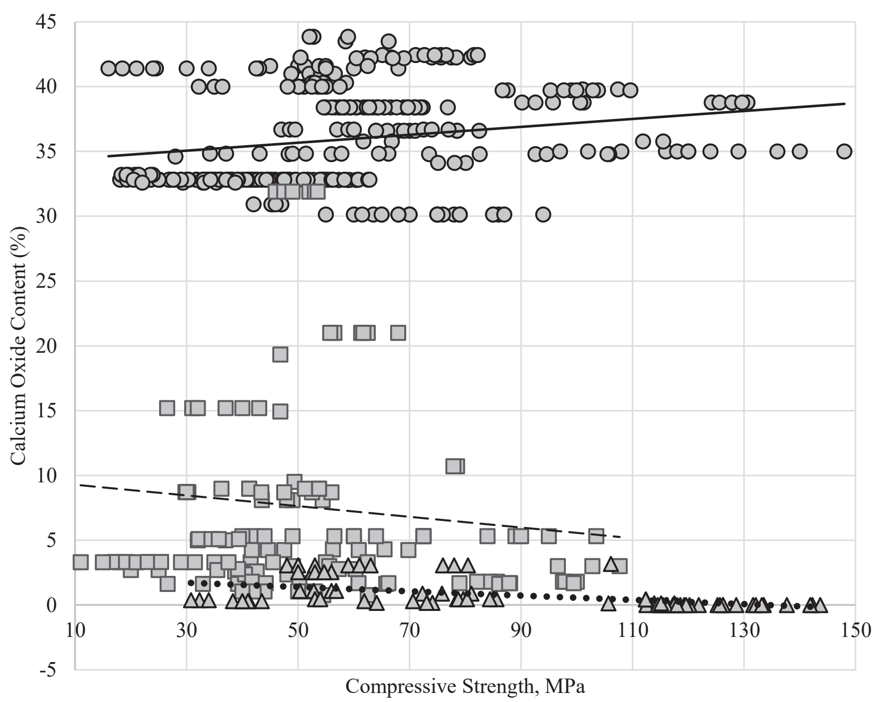


**Fig. 6a.** Calcium oxide content versus compressive strength of concrete incorporating pozzolans, ○, GGBS; □, fly ash; Δ, silica fume. Solid line, short-dashed line and long-dashed line represent the best fit for the calcium oxide content for GGBS, fly ash and silica fume.

been calculated for this approach. It is worth noting that the average compressive strength of concrete comprising optimum replacement levels of GGBS ranged from 49 MPa to 69 MPa, whereas the average compressive strength of concrete comprising optimum replacement levels of fly ash and silica fume ranged from 58 MPa to 61 MPa and 65–73 MPa respectively.

### 3.5. Sustainability assessment

The mix constituents for concrete models incorporating optimum replacement levels of the designated pozzolans summarised in Table 9 are used to estimate the $CO_2$ emissions generated through the production of such materials for practice. It should be noted that the $CO_2$ emissions that could be generated through the transportation, quarrying and extracting process have been omitted and the major focus have been given on the materials production itself. The $CO_2$ emissions factors of the binder, pozzolanic replacements as well as the fine and course aggregates, summarised in Table 6, are used for the analysis. The $CO_2$ emissions of concrete control as well as all the concrete models comprising optimum replacement levels of the designated pozzolans are exhibited in Fig. 7. It is evidently shown in Fig. 7 that the incorporation of the designated pozzolans yielded a substantial decrease in the $CO_2$

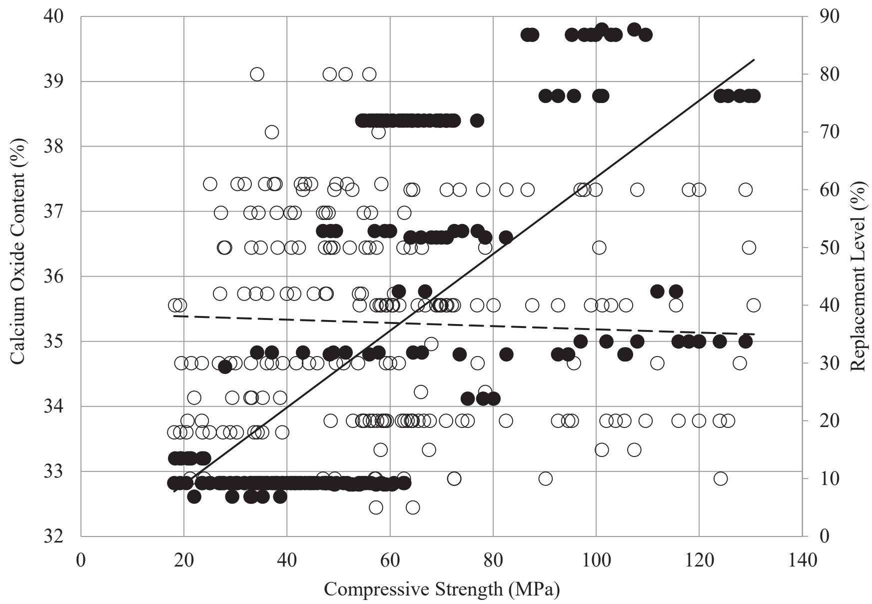


**Fig. 6b.** Calcium oxide content versus compressive strength of concrete incorporating GGBS Solid line represents the calcium oxide content and dashed line represent the replacement level. (Optimized GGBS data).

**Table 7**
(a): Descriptive statistics for concrete incorporating GGBS (Raw Dataset).

| | N | Minimum | Maximum | Mean | Standard Deviation |
|---|---|---|---|---|---|
| Replacement level (%) | 313 | 5.00 | 80.00 | 36.36 | 17.56 |
| Compressive strength (MPa) | 309 | 16.00 | 148.00 | 60.38 | 25.32 |
| Fineness ($m^2$/kg) | 280 | 350.00 | 750.00 | 441.85 | 68.31 |
| $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content (%), | 299 | 45.07 | 56.10 | 50.29 | 2.31 |
| Calcium oxide content (%) | 307 | 30.13 | 43.86 | 35.98 | 3.81 |
| Water: binder ratio | 311 | 0.20 | 1.00 | 0.42 | 0.15 |

Table 7(b): Descriptive statistics for concrete incorporating fly ash (Raw Dataset).

| | **N** | **Minimum** | **Maximum** | **Mean** | **Standard Deviation** |
|---|---|---|---|---|---|
| Replacement level (%) | 155 | 5.00 | 70.00 | 29.46 | 16.20 |
| Compressive strength (MPa) | 135 | 11.00 | 107.70 | 52.07 | 21.08 |
| Fineness ($m^2$/kg) | 125 | 253.40 | 680.00 | 392.39 | 98.53 |
| $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content (%), | 139 | 75.00 | 98.50 | 85.74 | 5.08 |
| Calcium oxide content (%) | 155 | 0.78 | 51.29 | 7.50 | 8.46 |
| Water: binder ratio | 155 | 0.25 | 0.75 | 0.40 | 0.10 |

Table 7(c): Descriptive statistics for concrete incorporating silica fume (Raw Dataset).

| | **N** | **Minimum** | **Maximum** | **Mean** | **Standard Deviation** |
|---|---|---|---|---|---|
| Replacement level (%) | 112 | 3.00 | 30.00 | 11.32 | 5.82 |
| Compressive strength (MPa) | 110 | 30.80 | 143.70 | 86.83 | 32.78 |
| Fineness ($m^2$/kg) | 65 | 1800.00 | 30000.00 | 19225.16 | 6969.93 |
| $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content (%), | 103 | 86.87 | 99.97 | 93.87 | 4.62 |
| Calcium oxide content (%) | 101 | 0.00 | 3.18 | 0.76 | 1.09 |
| Water: binder ratio | 110 | 0.16 | 0.64 | 0.31 | 0.11 |

**Table 8**
(a): Pearson correlation of the governing factors with respect to compressive strength.

| Pozzolan | | $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content (%) | Fineness ($m^2$/kg) | Water: binder ratio | Calcium Oxide content (%) |
|---|---|---|---|---|---|
| GGBS | Raw Data | 0.482 | 0.447 | 0.755 | 0.204 |
| | Optimized | 0.716 | 0.567 | 0.882 | 0.634 |
| FLY ASH | Raw Data | 0.157 | 0.211 | 0.693 | 0.096 |
| | Optimized | 0.287 | 0.356 | 0.754 | 0.176 |
| SILICA FUME | Raw Data | 0.230 | 0.011 | 0.861 | 0.484 |
| | Optimized | 0.547 | 0.251 | 0.931 | 0.818 |

Table 8(b): Replacement boundaries according to the factors.

emissions of these concrete models when compared that of the control (with no pozzolanic replacement). The results shown in Fig. 7 and therefore the considerable decrease in the $CO_2$ emissions of such concrete models are attributed to the reduced $CO_2$ emissions of the pozzolans used to replace the high energy and carbon intensive cement. Table 10 exhibits that the greater reduction in $CO_2$ emissions have been attained when 50% GGBS is incorporated in concrete. The 43% reduction attained in $CO_2$ emissions of concrete comprising GGBS is attributed to the practicability of the greater incorporation level of this pozzolanic substitute established as a result of the performance and correlation analysis conducted herein. The incorporation of fly ash and silica fume in concrete as a substitute to cement yielded a 31% and 13% reduction in the $CO_2$ emissions respectively. These vital reductions of $CO_2$ emissions play a key role in diminishing the greenhouse gas emissions [9,16].

## 4. Limitations

It is important to note that the accuracy of the data analysis results relies heavily on the preciseness of the experimental data harvested from

**Table 9**
Mix constituents of concrete incorporating optimum replacement levels of the designated pozzolans.

| | Type of Pozzolan | Pozzolan Content (%) | Cement Content (%) | Pozzolan Quantity (kg/m$^3$) | Cement Quantity (kg/m$^3$) | Fine Aggregates (kg/m$^3$) | Coarse Aggregates (kg/m$^3$) | Total (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|
| Control | **-** | 0 | 100 | 0 | 413 | 738 | 916 | 2067 |
| G15 | **GGBS** | 15 | 85 | 62 | 351 | 738 | 916 | 2067 |
| G50 | **GGBS** | 50 | 50 | 206 | 206 | | | 2067 |
| F10 | **Fly Ash** | 10 | 90 | 41 | 372 | 738 | 916 | 2067 |
| F35 | **Fly Ash** | 35 | 65 | 145 | 268 | | | 2067 |
| S5 | **Silica Fume** | 5 | 95 | 21 | 392 | 738 | 916 | 2067 |
| S15 | **Silica Fume** | 15 | 85 | 62 | 351 | | | 2067 |

the recent literature as well as the mix constituents reported in these studies. In this study the compressive strength of concrete aged from 28-days to 180-days are classified as short-term, and that compressive strength of concrete cured longer than 180 days are classified as long-term. It is worth noting that the study significantly be improved if there were more studies in the literature reporting the long-term properties of concrete comprising GGBS, fly ash and silica fume. The influence of the amorphousness on the strength development of concrete incorporating the designated pozzolans could not be investigated as the relevant data could not be extracted from the recent literature in the same approached used for the governing factors. Additionally, 56 data points representing the compressive strength of concrete comprising two or more combinations of pozzolans are omitted from the database and were not included in the further analysis.

**Table 10**
$CO_2$ Emission.

| | Replacement Levels (%) | $CO_2$ emission Scores (kg $CO_2$ / $m_3$) | Reduction (kg $CO_2$ / $m_3$) | Reduction (%) |
|---|---|---|---|---|
| Control | - | 424.0 | 0. | 0 |
| GGBS | 15 | 369.9 | 54.1 | 13 |
| | 50 | 243.5 | 180.5 | 43 |
| Fly Ash | 10 | 387.0 | 37.0 | 9 |
| | 35 | 294.5 | 129.5 | 31 |
| Silica Fume | 5 | 406.0 | 18.0 | 4 |
| | 15 | 370.0 | 54.0 | 13 |

## 5. Conclusions

The paper investigates the influence of the governing factors such as fineness, $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content, calcium oxide content, and water-to-binder ratio on the strength development of concrete comprising the designated pozzolans. The designated pozzolans in this paper are determined to be GGBS, fly ash and silica fume. There are numerous studies in the literature addressing the influence of such pozzolans on the strength development of concrete however the results reported by individual researchers unquestionably varies due to the dissimilarities often arise from the use of different standards and norms, the use of varying mix design principles, the use of different origin of the source materials which essentially yield to diverse properties of concrete to be attained both at the fresh and at hardened state. The authors therefore constructed a very large database on concrete comprising the designated pozzolans in order to comprehensively assess the influence of the governing factors on the strength development of concrete as well as to enable the authentic determination of the optimum replacement levels of such substitutes in practice.

The governing factors influencing the compressive strength of concrete incorporating pozzolans were meticulously investigated individually. This was essential to conduct as each factor has a diverse influence of the strength development of the particular pozzolan studied. The paper reveals that the governing factors, fineness, $SiO_2$, $Al_2O_3$, and

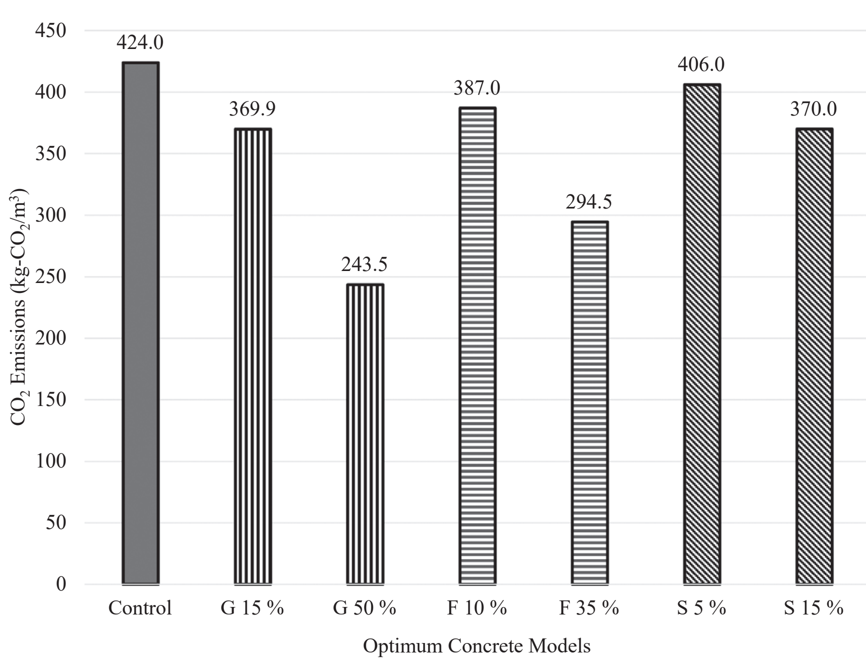


**Fig. 7.** $CO_2$ emissions of control and concrete models incorporating optimum replacement levels of GGBS, fly ash and silica fume.

$Fe_2O_3$ content, calcium oxide content, and water-to-binder ratio, studied herein had considerable influence on the compressive strength and strength activity index of concrete. The engineering performance as well as the boundary conditions carefully and individually assigned for each factor enabled the optimum replacement range of an individual pozzolan to be determined. Statistical analysis through the Pearson correlation factors were then conducted to validate the approach adopted in the first phase of the study in determining the optimum replacement levels of these pozzolans.

The results reported in this paper for instance enabled deeper insights into the factors affecting concrete to be gained. The low $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ content of GGBS for instance that initially appeared not to fulfil the norms with respect to the strength activity index later exhibited a considerably high calcium oxide content which had a great influence on accelerating both the hydration and pozzolanic reaction and hence yielded in a greater strength attainment of concrete.

The paper revealed a novel approach by bridging the database approach conducted through the performance analysis of each individual pozzolan with the statistical analysis by means of the Pearson correlations. The great agreement established between the both approaches provided high confidence not only on the right determination of the governing factors influencing the strength development of concrete but also on the determination of the precise range of replacement levels of the designated pozzolans in concrete.

The established concrete models comprising the optimum replacement levels of pozzolans are then used in the sustainability analysis through the $CO_2$ emissions. The study has shown that the considerable reduction on the $CO_2$ emissions of concrete is attained through the incorporation of the designated pozzolans. The $CO_2$ emissions reductions reported in this paper went up to 43% and suggested that the results stated in the present study are vital for diminishing the greenhouse gas emissions which has a positive impact on the ceasing the climate change. It must also be emphasised that the results documented in the paper also suggest more environmentally friendly production of construction materials for the industry.

## To the readers' information

The work presented is the outcome of the MSc thesis in the Sustainable Environment and Energy Systems (SEES) Graduate Program at the Middle East Technical University Northern Cyprus Campus. The lead author would like to acknowledge the Sustainable Environment and Energy Systems (SEES) Graduate Program at the Middle East Technical University Northern Cyprus Campus.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

Data will be made available on request.

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