

## Selection Tool for Concrete Mixes, a Sustainability-Based Approach

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**Abstract.** Over the past decade, the global population has experienced significant growth, a trend that is anticipated to continue in the coming years. This increase has led to a surge in demand for concrete, driving greater reliance on Portland cement production. Manufacturing Portland cement is widely recognized as both energy-intensive and a major contributor to carbon dioxide emissions, which is the main global warming contributor. Addressing these challenges requires innovative approaches to improve concrete sustainability, while maintaining its functionality. This research aims to develop more sustainable concrete by integrating waste materials and adopting environmentally friendly binders. Various concrete mixes were designed and evaluated based on mechanical properties as well as environmental impact. Materials used include recycled glass waste, ethylene vinyl acetate, and geopolymer binders. These materials were selected for their potential to reduce reliance on traditional cement, minimizing energy consumption and carbon emissions. The study's results highlight the feasibility of achieving significant reductions in environmental impact without compromising the mechanical performance of concrete. A sustainability ranking tool tailored to assess the sustainability of the mix based on its constituents, properties, and project-specific factors such as location is introduced. This tool provides a framework for promoting sustainable decision-making in construction. The tool was used to rank the mixes developed in this study based on different countries. Ultimately, this study seeks to advance the adoption of eco-conscious practices within the construction industry.

**Key words:** Portland cement concrete; Sustainability; Sustainability Index; Geopolymer; Waste Materials

### 1. Introduction

Roughly 10% of CO<sub>2</sub> emissions linked to energy usage around the globe are connected to the entire process of producing and disposing of cement and concrete. The main culprit for these emissions is the cement production itself (Griffiths et al., 2023). To combat pollution and the growing number of landfills caused by the significant amounts of waste produced worldwide, it is essential to find sustainable solutions. One approach is to utilize some of these waste materials to create environmentally-friendly concrete mix, such as recycled waste glass (Qaidi et al., 2022; Gautam et al., 2012; Ismail & Al-Hashimi, 2009), ethylene vinyl acetate (EVA) (Khan et al., 2019-1; Khan et al., 2019-2; Farhoud et al., 2018), and slag (Osborne, 1999; Divsholi et al., 2014; Gruyaert et al., 2010). While previous literature has extensively explored the isolated use of alternative binders and waste materials such as recycled glass, EVA foam, and ground granulated blast furnace slag, there remains a distinct lack of comprehensive frameworks evaluating these constituents simultaneously against multi-criteria sustainability metrics. Furthermore, existing studies predominantly focus on mechanical performance rather than providing adaptable, geographically sensitive assessment tools. To bridge this research gap, this study introduces a novel,

customizable 'Sustainability Index'. This tool not only evaluates the synergistic effects of integrating multiple waste streams into Portland and geopolymer concrete matrices, but it also provides a quantitative framework that adapts to specific regional and project requirements. Ultimately, this study seeks to advance the adoption of eco-conscious practices within the construction industry by delivering a pragmatic decision-making instrument.

## **2. Literature review**

### ***2.1. Geopolymer Concrete***

Geopolymer concrete is an amorphous alkali aluminosilicate (Almutairi et al., 2021) with strength dependent on several factors. Higher compressive strength is achieved through increased NaOH molarity, higher sodium silicate-to-sodium hydroxide ratios, and curing temperatures between 30–90°C. While strength increases with curing time (6–96 hours), gains become insignificant after 48 hours. Admixtures can improve workability with minimal strength impact (Hardjito et al., 2004), though higher NaOH molarity reduces slump (Bellum et al., 2022). To address the high emissions of Portland cement, Singh et al. (2020) reviewed geopolymer binders synthesized from aluminosilicate sources like fly ash or slag. They found that geopolymer concrete is a viable alternative under both ambient and steam curing, achieving optimal results at a sodium silicate-to-sodium hydroxide ratio of 2. Verma et al. (2022) further highlight the material's cost-effectiveness, durability, and eco-friendliness due to its use of industrial waste. Consequently, geopolymer concrete is highly suitable for major infrastructure projects, including bridges, high-rises, and dams.

### ***2.2. Effect of Slag Replacement on the Mechanical Properties of Fly Ash Based Geopolymer Concrete***

Kathirvel et al. (2013) developed geopolymer concrete using fly ash and ground granulated blast furnace slag (GGBFS) as a sustainable cement alternative. By testing 12 mixes, they determined that compressive strength improved as the percentage of GGBFS increased. Furthermore, a sodium silicate-to-sodium hydroxide ratio of 1.5 yielded superior results compared to a ratio of 1. Similarly, Bellum et al. (2022) observed that while adding GGBFS decreased workability by 12–37%, it significantly improved mechanical properties. Specifically, compressive strength increased by 5–10 MPa for every 10% increase in GGBFS. 40% GGBFS replacement was identified as optimal. Combining high GGBFS content with a 10 M NaOH solution enhanced durability and created a denser microstructure due to improved pore filling.

### ***2.3. EVA Foam as Coarse Aggregate Replacement in Concrete***

Farhoud et al. (2018) investigated using toxic EVA waste from the footwear industry as a concrete aggregate to mitigate environmental risks. Testing shredded EVA particles (9.5mm, 19mm, and 38mm) as partial coarse aggregate replacements, they determined that a 5% replacement with the 9.5mm size yielded the highest compressive strength. Alternatively, using EVA as an admixture was found to enhance workability, improve flexural strength, and increase compressive strength by up to 19%, though it retarded setting time (Khan et al., 2019-1). EVA additives also facilitated the development of self-compacting concrete (Khan et al., 2019-2).

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## 2.4. Recycled Glass as Fine Aggregate Replacement in Concrete

Adawy and Wang (2015) investigated replacing fine aggregate with 15–40% crushed waste glass to address landfill issues. They concluded that a 30% replacement was effective, increasing compressive strength by 9% at 7 days and 6% at 28 days. However, broader reviews suggest an optimal replacement of only 20% (Qaidi et al., 2022), noting that glass generally reduces workability while density results remain inconclusive. Gautam et al. (2012) supported the 20% threshold, observing marginal strength gains up to that point but a decrease at 30% replacement.

## 3. Experimental Work

### 3.1. Materials

- Type I Ordinary Portland Cement: with a Blaine fineness of 340 m<sup>2</sup>/kg and a specific gravity of 3.15.
- Fine aggregate: natural sand, with saturated surface dry (SSD) specific gravity of 2.57 and fineness modulus of 2.62.
- Coarse aggregate: dolomite, with SSD specific gravity of 2.61.
- Water: Ordinary tap water was used in mixing and curing.
- Fly ash: Class F fly ash with specific gravity 2.5.
- Sodium Hydroxide (14 molarity) and Sodium Silicate (50% concentration)
- Crushed glass: Green-dyed glass, shredded and sieved to be used as partial replacement of fine aggregates. The green color is due to the presence of iron, chromium and copper. The specific gravity of this glass was 2.5.
- Steel Slag: Well-graded crushed slag was used. Slag contained silicon dioxide (SiO<sub>2</sub>) content within the range of 35%- 40%.
- EVA Foam: EVA stands for Ethylene Vinyl Acetate, which is a copolymer. It was shredded into 19mm sized particles and used as partial replacement of coarse aggregates.

### 3.2. Concrete mix designs

#### Portland Cement Concrete Mixes

A control Portland cement mix (w/c ratio 0.6) was designed to target a strength of 30 MPa. The reason this target compressive was chosen because this is the most commonly used compressive in Egypt. Three experimental mixes incorporated waste materials: shredded EVA foam partially replaced coarse aggregates (based on literature findings), while crushed glass replaced fine aggregates at doses of 20% and 30%, reflecting previous studies that identified this range as optimal. All mixing and casting followed ASTM C192/C192M standards, with detailed mix proportions presented in Table 1.

**Table 1. Ordinary Portland Cement Concrete Mix Design**

Quantities by weight (kg/m <sup>3</sup> )	Mix 1	Mix 2	Mix 3	Mix 4
Coarse Aggregates	1175	1175	1175	1080
Fine Aggregates	635	510	440	635
Cement	300	300	300	300
Water	185	185	185	185
Glass	0	130	195	0
EVA-foam	0	0	0	60
Percentage glass by weight of fine aggregate	0%	20%	30%	0%
Percentage EVA-foam by weight of coarse aggregate	0%	0%	0%	5%

## Fly Ash based Geopolymer Concrete Mixes

Seven fly ash based geopolymer concrete mixes were prepared. Mixes 5 through 7 were prepared without the inclusion of wastes. Mixes 8 and 9 included slag as replacement of fly ash, as guided by the findings from the literature review and logical progression based on the compressive strength outcomes. Mixes 8 and 9 were based on mix 7, where in mix 8, slag was added as 40% replacement of fly ash. In mix 9, slag was added as 60% replacement of fly ash. Additionally, based on the results obtained from the ordinary Portland cement concrete mixes with the incorporation of wastes, geopolymer concrete mixes with waste glass were also prepared. The specific mix designs, including the different materials used and their respective weights per m<sup>3</sup>, can be found in Table 2.

**Table 2. Geopolymer Concrete Mix Design**

Quantities by weight (kg/m <sup>3</sup> )	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11
Aggregates	1485	1500	1430	1430	1430	1365	1325
Fly Ash	590	680	695	415	280	620	680
Alkaline Activators	255	255	325	392	392	290	255
Glass	0	0	0	0	0	135	160
Slag	0	0	0	280	415	0	0
Sol./binder	0.35	0.31	0.35	0.35	0.35	0.35	0.31
NaOH/NaSi	1	1.67	1	1	1	1	1.67
Percentage glass by weight of aggregate	0%	0%	0%	0%	0%	10%	12.5%
Percentage slag by weight of fly ash	0%	0%	0%	40%	60%	0%	0%

### 3.3. Experimental Testing

#### Fresh concrete tests

- Unit weight: According to ASTM C138.
- Slump: According to ASTM C143.
- Air content: Air content per mix was tested in accordance to ASTM C231.

#### Compressive strength test

The compressive strengths of the 11 concrete mixes were evaluated following the guidelines outlined in BS1881. For each mix, three cubes of dimensions 15cm x 15cm x 15cm were cast and then subjected to compressive strength testing at specific time intervals (7 days, 14 days, 21 days, and 28 days) using a universal testing machine until failure occurred. All mixes were cured in a moist room until the day of testing.

## 4. Results and Analysis

### 4.1. Fresh Concrete Tests

The results of the fresh concrete tests conducted on all mixes are presented in Table 3. It can be seen from the results that the inclusion of waste materials had an impact on the workability of concrete when Portland cement is used. The conventional Portland cement mix (Mix 1) had a slump of 50mm, which decreased to 35mm and 25mm when waste glass and EVA foam were integrated, respectively. This decrease in slump can be attributed to the rougher surface texture of the waste materials and the water-absorbing characteristics of the EVA foam. In contrast, the geopolymer mixes exhibited the highest slump of 250mm. However, these mixes demonstrated poor slump retention, leading to a minimal setting time and workability that could not be maintained. Despite this, the unit weight results for all mixes fell within an acceptable range, with

mix 4 having the lowest unit weight of 2160 kg/m<sup>3</sup>. Lastly, the air content values ranged from 1.5% to 3%, with no significantly high or low values observed across the mixes.

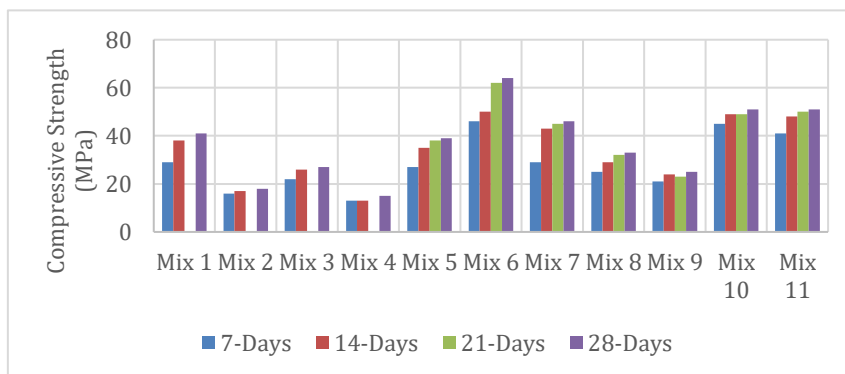
**Table 3. Fresh Concrete Results**

Fresh	Slump (mm)	Unit Weight (kg/m <sup>3</sup> )	Air Content (%)
Mix 1	50	2205	3.0
Mix 2	25	2300	2.0
Mix 3	35	2390	2.5
Mix 4	25	2160	2.5
Mix 5	250	2330	1.5
Mix 6	250	2435	1.5
Mix 7	250	2450	1.5
Mix 8	250	2455	1.5
Mix 9	250	2450	1.5
Mix 10	250	2403	1.5
Mix 11	250	2420	1.5

## 4.2. Compressive Strength Test

As shown in Figure 2, the compressive strength results for the Portland cement mixes were obtained at 7, 14, and 28 days, while for the geopolymer mixes, the results were measured at 7, 14, 21, and 28 days. The strength evolution of all mixes can be observed. Figure 2 indicates that the incorporation of waste materials typically results in a decrease in compressive strength. This is likely because many of the waste materials are not as strong as the virgin aggregates used in concrete production. However, the impact of this reduction is less significant in the geopolymer mixes. The highest compressive strength achieved after 28 days was 64 MPa, observed in Mix 6, which is a geopolymer mix with no waste. On the other hand, the lowest compressive strength achieved after 28 days was 15 MPa in Mix 4, which is the Portland cement mix with EVA foam.

It can be observed that the geopolymer mixes gained higher early strength at 7 days, then the rate of increase in strength was reduced significantly after 21 days.



**Fig 2. Comprehensive Strength Results**

## 5. Developing Criteria for the “Sustainability Index”

To create environmentally friendly concrete, it was essential to establish a set of criteria to assess the degree of sustainability for each concrete mix. These criteria are designed to be adaptable, allowing for adjustments based on the specific application, country, and project requirements. The proposed sustainability index is aimed to be used for comparison purposes between a set of mixes proposed for use in a project. The chosen criteria are primarily based on the mechanical properties of the concrete mixes, impact on the environment, and cost-effectiveness. Other

potential criteria, such as the biodegradability of waste materials and energy consumption, may also be considered. This is a simplified technique that can be used in places where life cycle cost assessment is not done or when there is no available data. The sustainability index for the concrete mixes was evaluated in four different countries, which are Egypt, Spain, Indonesia, and the USA. Each mix was assessed according to the selected criteria in these countries.

Six key criteria have been identified to gauge the sustainability index of the concrete mixes: adequate mechanical properties, reduced carbon dioxide emissions, effective utilization of waste materials, decreased reliance on natural resources, cost-effectiveness, and minimized hazardous waste. The importance of each criterion is determined based on the nature of the concrete mix or the specific country it will be used in. To achieve this, weights are assigned to each criterion, allowing for flexibility in adjusting these weights according to the country and project requirements, provided that the total for these weights add up to 100 percent. The authors provided a range of values for the distribution of weights among the different criteria based on the importance of each criterion. These weighted percentages were utilized to formulate a versatile "Sustainability Index" equation. The recommended ranges, along with the distribution of weights chosen for this study are presented in Table 4.

**Table 4. Weighted criteria percentages for sustainability index**

Criterion	Weight Range	Selected Weight	Symbol
Mechanical properties	15 – 25%	25%	$W_{MP}$
Carbon dioxide emissions	20 – 30%	25%	$W_{CO2}$
Waste incorporation	20 – 30%	25%	$W_{WI}$
Natural resource reduction	5 – 15%	5%	$W_{NR}$
Cost effectiveness	10 – 25%	15%	$W_{CE}$
Hazardous waste reduction	5 – 15%	5%	$W_{HW}$

The Sustainability Index is achieved by calculating the six different criteria and then multiplying each of them by the weight presented in Table 4. The total of all factors will yield a sustainability score out of 100. The higher the score, the more sustainable the mix is. The calculation is presented in Equation 1.

$$SI = W_{MP} * MP + W_{CO2} * CO2E + W_{WI} * WI + W_{NR} * NR + W_{CE} * CE + W_{HW} * HW \quad (1)$$

### 5.1. Mechanical Properties

Mechanical properties are assessed based on the results of the compressive strength test conducted on the concrete mixes in this study. The calculation involves dividing the compressive strength of the specific mix by the highest compressive strength achieved among all mixes (Equation 2).

$$MP = \frac{\text{compressive strength of relevant mix}}{\text{maximum compressive strength of all mixes}} \quad (2)$$

### 5.2. Carbon Dioxide Emissions

The calculation of carbon dioxide emissions is dependent on the level of carbon dioxide generated during cement production, which varies from one country to another based on regional manufacturing practices. Thus, the specific amounts of carbon dioxide emitted per ton of cement for each country have been adjusted to reflect accurate industry averages: Egypt produces 820 kg of CO<sub>2</sub> per ton of cement, Spain (representing the European average) produces approximately 650 kg of CO<sub>2</sub> per ton of cement (CEMBUREAU, 2021), the U.S. produces roughly 900 kg of CO<sub>2</sub> per ton of cement (Portland Cement Association, 2021), and Indonesia produces around 680 kg

of CO<sub>2</sub> per ton of cement (International Energy Agency, 2022). The equation involves multiplying the weight of cement in the mix by the country-specific CO<sub>2</sub> production to get the CO<sub>2</sub> emitted by each mix

$$CO_2E = 1 - \left( \frac{CO_2 \text{ emitted by the relevant mix}}{\text{maximum } CO_2 \text{ emitted by all mixes}} \right) \quad (3)$$

### 5.3. Incorporation of Wastes

The waste materials incorporated into the concrete mixes include glass wastes, slag, EVA foam, and fly ash. The waste percentages in each country are determined by dividing the weight of each waste material by the total weight of the four wastes present in that country. The percentages are presented in Table 5.

**Table 5. Waste Percentage/Country's Total Waste Percentage**

Waste / Country (%)	Egypt	Spain	Indonesia	USA
Glass (%)	25%	15% (Picvisa, 2020)	12%	6%
Slag (%)	0.7% (Trading economics, 2022)	2% (Spain Steel Production, 2022)	0.2% (Statista, 2021)	0.1% (Statista, 2022)
EVA foam (%)	0.2% (Farhoud et al., 2018)	0.1%	0.1%	0.2%
Fly Ash (%)	74%	83%	88%	95% (EPA, 2022)

Equation 4 is used to calculate the waste incorporation factor for each waste type. Equation 5 is used to calculate the overall waste incorporation factor.

$$WI_i = (\text{waste \% in country}) * \frac{\text{waste weight in mix}}{\text{maximum waste weight in all mixes}} \quad (4)$$

$$WI = \sum_1^n WI_i \quad (5)$$

Where "n" is the number of wastes included.

### 5.4. Natural resources

In this study, the focus was on considering water as the primary natural resource. The water scarcity weight for each country was taken into account to decide on the suitable weight for each country. The classification presented in Table 6 was used (World Population Review, 2023). A weight of 1 – 5 was given, corresponding to the five levels. A maximum weight of 5 was assigned to indicate very high-water scarcity. It was found that Egypt and Spain both have high water scarcity. The USA has low to medium water scarcity. Finally, Indonesia was found to have medium to high water scarcity as shown in Table 7 (World Population Review, 2023).

**Table 6. Water Scarcity Levels and Their Corresponding Weights**

Water Scarcity Level	Withdrawals to Supply Ratio	Weight
Low	<10%	1
Low - Medium	10 - 20%	2
Medium - High	20 - 40%	3
High	40 - 80%	4
Very High	>80%	5

**Table 7. Water Scarcity per Country**

Country	Water scarcity	Water scarcity weight
USA (World Population Review, 2023)	Low - Medium	2
Spain (World Population Review, 2023)	High	4
Egypt (World Population Review, 2023)	High	4
Indonesia (World Population Review, 2023)	Medium - High	3

To calculate the natural resource availability, the water scarcity percentage in each country is subtracted from five, which corresponds to the highest possible water scarcity value (Equation 6).

$$NR = \frac{5 - \text{water scarcity \% of the country}}{4} \quad (6)$$

### 5.5. Cost effectiveness

Cost is a critical factor in assessing the practicality of a concrete mix. It is derived from the materials utilized and is calculated by dividing the cost per cubic meter (m<sup>3</sup>) by the highest cost among all the mixes per m<sup>3</sup> in the country of interest (Equation 7).

$$CE = 1 - \left( \frac{\text{cost of mix}}{\text{maximum cost of all mixes}} \right) \quad (7)$$

### 5.6. Hazardous conditions

The assessment of hazardous conditions is based on extensive research conducted to determine the hazardous levels of the materials used. The assessment of hazardous conditions is based on the chemical toxicity, occupational handling risks, and environmental leaching potential of the materials used. Natural aggregates and glass waste are chemically inert and pose negligible environmental risks, justifying a 'Low' hazard weight of 1.0. Geopolymer binders and EVA foam are assigned a 'Medium' hazard weight of 2.5. Geopolymers necessitate the use of highly caustic alkaline activators (such as 14 molarity sodium hydroxide), which pose significant occupational handling hazards. EVA foam is a synthetic copolymer whose degradation and micro-particulate dust require careful environmental management. Finally, steel slag is assigned a 'High' hazard weight of 5.0 due to its high alkalinity and the potential for leaching heavy metals into soil and groundwater if not properly stabilized (Proctor et al., 2000). Table 8 below illustrates the hazardous levels of each material:

**Table 8. Waste Hazard Weight**

Material	Hazard Level	Hazard Weight
Coarse aggregates	Low	1.0
Fine aggregates	Low	1.0
Glass waste	Low	1.0
Geopolymer	Medium	2.5
EVA foam waste	Medium	2.5
Slag	High	5.0

The equation is obtained by getting the average level of hazardousness of all materials included in the mix:

$$HW = \frac{5 - \left( \frac{\sum_{i=1}^n \text{Hazard Weight}_i}{n} \right)}{4} \quad (8)$$

Where:

“n” is the number of material hazards included in the analysis

“Hazard Weight<sub>n</sub>” is the value presented in Table 8.

The developed equation is then used to determine the “Sustainability Index” of the mixes for each country and yielded the results presented in Figure 3.

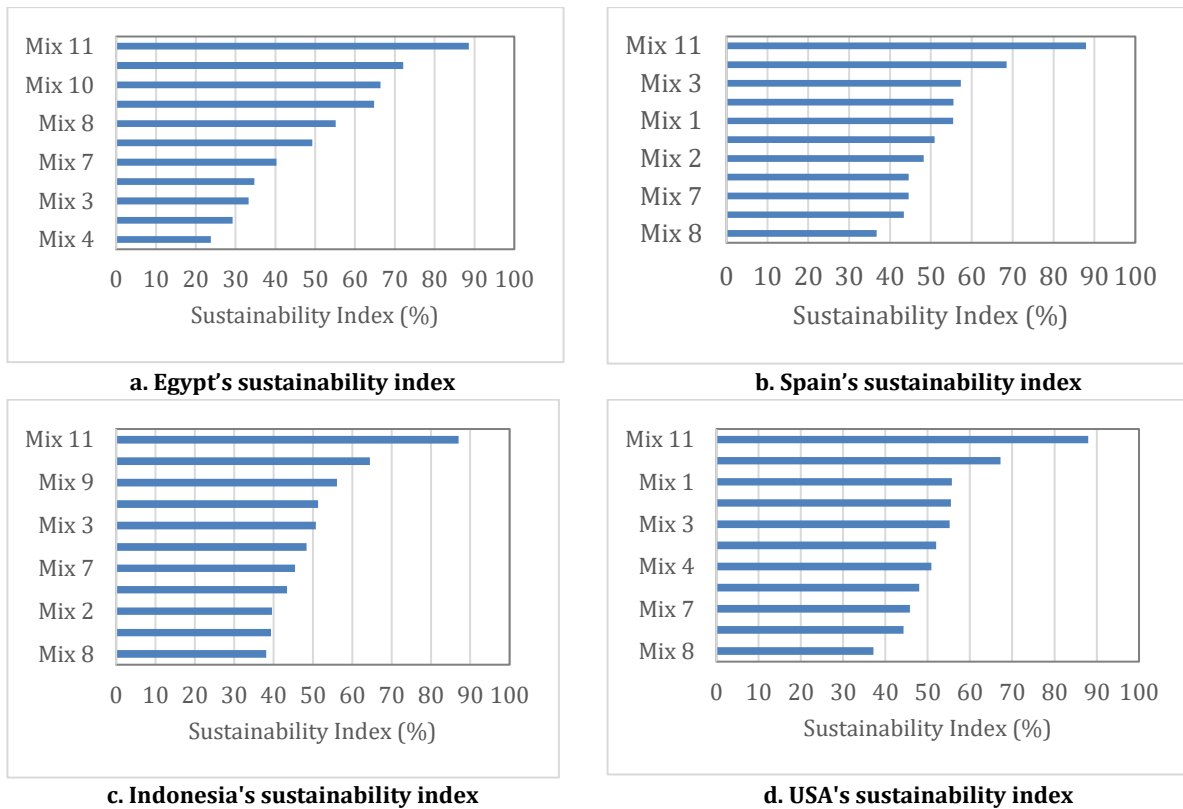


Fig 3. Sustainability index for different countries

## 6. Conclusions

Based on the scope of this work as well as the materials and parameters involved in this study, the following conclusions can be warranted:

- For the Portland cement concrete mixes, the use of glass and EVA foam negatively affected the strength of concrete. The reduction ranged between 35 to 65% of the control sample's strength, The modified concrete mixes did not meet the target strength. To achieve the desired strength, the w/c has to be reduced,
- All the geopolymer concrete mixes met and exceeded the target strength, except for mix 9, which had the higher slag dosage.
- In geopolymer concrete, changing the solution to binder ratio within the range of 0.3-0.35 had no impact on compressive strength, while increasing the sodium hydroxide to sodium silicate ratio led to higher strength results.
- The study also demonstrated the feasibility of producing various types of sustainable concrete using locally available materials, achieving a balance between mechanical properties and environmental friendliness.
- The proposed "sustainability index" takes into consideration some simple environmental aspects and can be used as a comparative tool to identify the more sustainable mix among a group of mixes. As the environmental constraints and amount of pollution due to production differ from one country to the other, the tool was designed to be sensitive to the project location.
- The users have the flexibility to tweak the equation according to their needs.

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