Ceramics

Assessment of environmental, economic and technical performance of geopolymer concrete: a case study

Rafia Firdous[1],* , Morteza Nikravan[1], Raoul Mancke[1], Manuel Vöge[2], and Dietmar Stephan[1]

[1] *Department of Civil Engineering, Building Materials and Construction Chemistry, Technische Universität Berlin, Gustav-Meyer-Allee 25, 13355 Berlin, Germany*
[2] *Beton und Naturstein Babelsberg GmbH, Walter-Klausch-Straße 17A, 14482 Potsdam, Germany*

ABSTRACT

Although several studies report the CO_2 reduction obtained from alkali-activated materials/geopolymers, only a few investigate their engineering, environmental and economic aspects. The present paper provides an evaluation approach to address these three major aspects of geopolymer concrete by choosing three scenarios for industrial precast applications. Using the analytical hierarchy process, a single sustainability score was determined for three scenarios using technical, environmental and economic parameters. Such sustainability sensitivity analysis led to decision-making for various scenarios. This case study provides an example of reaching these parameters for choosing suitable concrete mixtures for a given application or requirements. The technical and environmental results showed that a wide range of late and early age compressive strength could be achieved by changing the mix composition and proportions. However, all the geopolymer concrete samples exhibited a lower environmental footprint than OPC concrete.

Introduction

The increasing awareness of global warming and resource consumption has led to the development of sustainable and resource-efficient technologies in many industries. The increasing demand for infrastructure development around the globe is tremendously enhancing concrete usage [1]. Worldwide,

approximately 30 billion metric tons of concrete are used annually [2]. Cement is the binder in the concrete and its production is out of the major sources of global warming by producing up to 7% of global anthropogenic emissions [3]. Approximately 1 ton of CO_2 is produced for every ton of cement clinker production [4]. Burning of calcium carbonate for production of cement clinker is responsible for 60% of CO_2 emissions, whereas the rest is emitted due to

---

Handling Editor: M. Grant Norton.

Address correspondence to E-mail: rafia.firdous@tu-berlin.de

burning of fuel for kiln process [1]. Moreover, cement production is accountable for the consumption of natural resources and energy usage. Almost 5% of total global industrial energy is consumed for cement production [5]. Therefore, the exponentially increasing consumption of cement and concrete is one of the major factors of the deterioration of the environment and global warming.

The newly formed environmental protection policies aim to reduce these emissions by 55% by 2030 and achieve a neutral climate by 2050 [6]. In this regard, several affords have already been made to reduce the environmental impact of the construction industry by using various ways, such as reducing the consumption of clinker and/or using alternative binders. Some examples include ordinary Portland cement (OPC) with partial replacement of supplementary cementitious materials (SCM), supersulphated cement and alkali-activated materials/geopolymers. Alkali-activated materials (AAM) and/or geopolymer (GP) have gained much interest in the last decades because of the promising reduction in CO_2 emissions compared to OPC-based binders. These binders are synthesised solely by the reaction of aluminosilicate raw material with an alkaline solution [7, 8]. Several studies have shown the potential of several aluminosilicate precursors for producing these binders, including the materials from natural or artificial sources such as industrial, agricultural or municipal wastes [9]. The researchers have thoroughly investigated the reactivity of these precursors by using several combinations of the alkaline solutions and the aluminosilicate raw material [9]. However, only a few have studied the properties of these binders in mortar or concrete form and have thoroughly calculated the environmental impact.

Dontriros et al. [10] studied the physical–mechanical, life-cycle assessment and economic feasibility of the geopolymer bricks prepared with palm oil fuel ash and concrete residue and showed a payback period of 3.88 years [10]. However, the study focussed on the production of geopolymer pastes for the production of bricks and a comparison with a reference sample for life-cycle assessment was beyond the scope of the paper [10]. The combination of fly ash and metakaolin resulted in higher compressive strength; however, the minimum environmental impact values were obtained for geopolymers developed with a combination of fly ash and slag

[11]. A study comparing the environmental impact of the same compressive strength of alkali-activated slag and OPC concrete confirmed the advantage of reduction of CO_2 emissions by use of alkali-activated slag [12]. Similarly, another study evaluated the environmental impact of four different concrete recipes with comparable compressive strengths and compared them to a conventional concrete recipe [13]. Results showed that despite a quite high amount of alkaline activator used in alkali-activated fly ash concrete with natural aggregate, it had the overall best environmental performance in the evaluated scenarios [13]. In a comparable case study, the authors highlighted the importance of allocations for aluminosilicate raw materials such as fly ash and slag to calculate the environmental impact [14]. The environmental impact of alkaline solutions such as sodium silicate solution was dominant in alkali-activated materials [15]. The use of volcanic ash and blast furnace slag for the production of alkali-activated concrete did not only exhibit comparable mechanical properties to OPC concrete but also lowered the global warming potential by 44.7% [16]. In general, it is found in the literature that an increase in compressive strength is associated with higher CO_2 emissions. However, the increase in the compressive strength and associated increase in the CO_2 emissions was found to be significant for OPC concrete compared to alkali-activated concrete (AAC) made from alkali-activated blast furnace slag [17]. Although the additional process such as heat curing to achieve higher compressive strength for alkali-activated materials can have an influence [18]. Special applications such as alkali-activated masonry blocks compared to compacted stabilised engineered soil & cement block showing comparable mechanical and durability characteristics as an ordinary concrete block showed better embodied carbon and water consumption for stabilised soil blocks [19].

The purpose of these prior studies was to demonstrate the potential, whereas the purpose of this study is to provide a strategy for achieving the environmental, technical and economic objectives of a given application. We analyse real developed and executed concrete mixtures for their workability and compressive strength and then calculate the LCA and sustainability of those mixtures. Several raw materials are used to produce alkali-activated concretes such that varying compressive strengths at various ages are obtained. To determine the suitability of

Table 1 Oxide composition of raw materials

Oxides	CEM-I	CA	FA	GGBFS	SF	MK	LS
LOI*	2.55	0.28	5.35	− 1.01**	3.68	10.18	41.61***
Al_2O_3	4.93	70.92	22.69	10.70	0.17	38.55	1.14
CaO	63.05	28.33	4.59	39.46	0.35	0.00	40.09
Fe_2O_3	2.89	0.17	6.25	0.27	0.02	1.28	0.45
K_2O	1.06	BR	1.77	0.71	0.32	0.19	0.29
MgO	1.69	0.20	1.71	8.65	0.20	0.08	11.34
Mn_2O_3	0.05	0.01	0.06	0.16	0.03	0.01	0.04
Na_2O	0.23	0.23	0.56	0.38	BR	0.00	BR
P_2O_5	0.07	BR	1.10	BR	0.04	0.14	0.03
SiO_2	19.39	0.17	54.35	37.53	95.56	47.51	5.57
SO_3	3.83	0.02	0.23	2.56	0.02	0.05	0.04
SrO	0.15	BR	0.16	0.07	0.04	0.00	BR
TiO_2	0.21	0.01	1.11	0.79	BR	1.41	0.06

*LOI stands for loss on ignition at 1000 °C, **Negative LOI value is due to oxidation of sulphur, ***High LOI due to calcium carbonate decomposition, BR stands for below measurement range

various concrete mixtures, technical, environmental and economic aspects are considered. This case study demonstrates how these factors can be considered to find the suitability of concretes for desired application scenarios.

Materials and methods

Materials

In this research study, different primary and secondary raw materials in various combinations have been used to develop several concrete recipes. Unlike ground granulated blast furnace slag (GGBFS), fly ash (FA) can be used as a precursor for AAM in obtained form. Therefore, fly ash (FA) was used as the base material for all concrete recipes to keep the environmental impact low. Other materials used include GGBFS, silica fume (SF), metakaolin (MK), dolomitic limestone (LS), CEM-I type Portland cement and calcium aluminate cement (CA).

As the geopolymer concrete recipes are designed for industrial application, therefore, to attain high early strength development, potassium silicate solution was used in most of the recipes [9]. Other solutions such as sodium silicate, NaOH (16 mol/kg) and KOH (16 mol/kg) were also used. Potassium silicate solution had a silica modulus of 1.7 mol/mol with SiO_2 equal to 23.4 wt.%, K_2O equal to 21.7 wt.% and H_2O equal to 55 wt.%. Sodium silicate solution had a silica modulus of 2.12 mol/mol with SiO_2 equal to

30.2 wt.%, Na_2O equal to 14.7 wt.% and H_2O equal to 55 wt.%.

Materials characterisation methods

All the used materials were characterised by X-ray fluorescence analysis (XRF) and X-ray diffraction analysis (XRD) for their chemical and mineralogical composition. The chemical composition determined using WD-RFA PW 2400, PHILIPS is provided in Table 1 and the mineralogical composition was determined using Empyrean PANalytical diffractometer with Ni filter and CuKα radiation ($\lambda = 1.54$ Å), operating in continuous mode at 40 kV and 40 mA, at a resolution of 0.0131° and a speed of 0.0176°/s, in a range of 5°–65° 2θ. The phase evaluation was performed using HighScore Plus software with ICDD and ICSD databases and is provided in Fig. 1. Several crystalline, semi-crystalline to amorphous phases were observed in all raw materials and are labelled in Fig. 1.

The physical characteristics such as fineness and particle size distribution were determined by the Blaine air permeability method [20] and laser granulometric analysis using Mastersizer 2000 of Malvern Instruments, respectively. For the useability of the concretes at an industrial scale, all raw materials were used as supplied without further treatments. Table 2 presents the density, Blaine fineness, d_{10}, d_{50} and d_{90} of all the raw materials and Fig. 2 presents the particle size distribution curves of all raw materials.
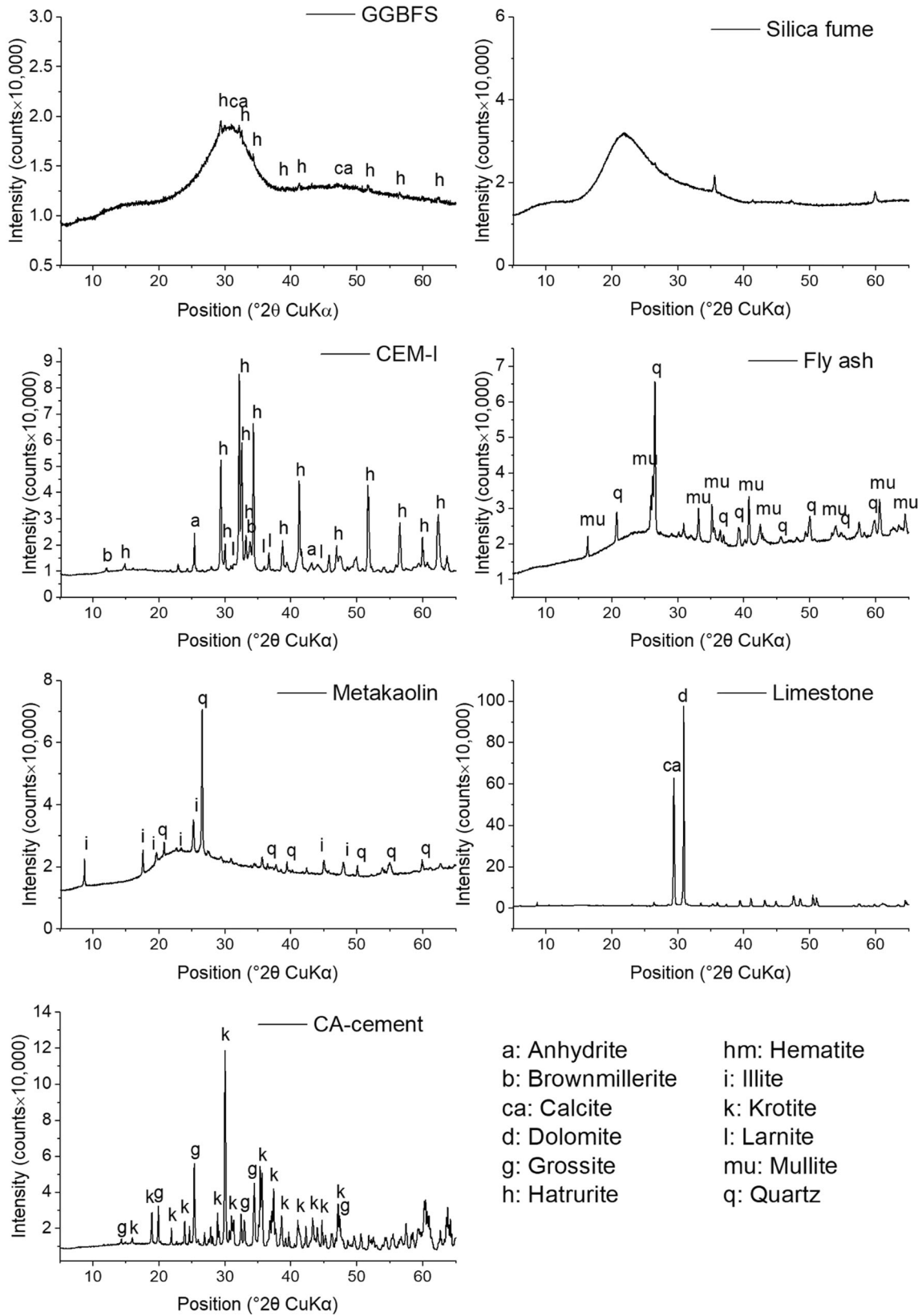
Figure 1 Mineralogical composition as determined by XRD.

Table 2 Blaine fineness, d_{10}, d_{50}, d_{90} and particle density of all raw materials

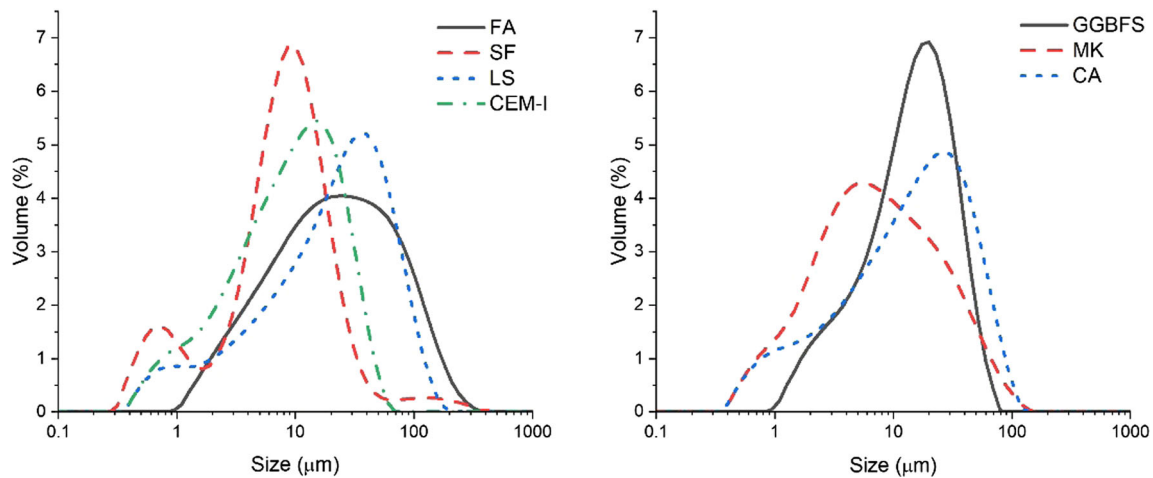| Sample name	d_{10} (μm)	d_{50} (μm)	d_{90} (μm)	Particle density (g/cm³)	Blaine Fineness (cm²/g)
CEM-I	1.5	8.6	25.7	3.1	4431
CA	1.6	13.9	47.1	3.0	3815
FA	3.6	20.0	88.0	2.3	3391
GGBFS	3.3	13.9	33.7	2.9	3382
SF	0.9	7.5	20.6	2.2	> 6000
MK	1.4	6.6	33.0	2.6	5892
LS	2.2	20.7	65.9	2.8	3116

Figure 2 Particle size distribution of all raw materials.

Concrete mixtures

The concrete mixtures were designed to meet the strength classes according to EN 206–1 [21] and to fit for the use as precast concrete elements such as concrete blocks in 3 different scenarios. Three scenarios of low, medium and high compressive strength concrete for different applications are studied and described later. To meet the needs of industrial application, the concrete recipes should attain enough early strength to be demoulded after one day. It is worth mentioning here that the selected reference mixture of OPC was chosen as its commonly used mixture design in industrial applications, even though its performance is far better than desired application requirements. All the investigated concrete recipes are given in Table 3. In the OPC mix design, cement content is lower (330 kg/m³) and limestone is added to reduce the environmental burden. All the geopolymer concrete recipes were designed at a constant binder content of 500 kg per 1 m³ of concrete. The binder content consisted of all the precursors used for geopolymer synthesis, i.e. FA, GGBFS, MK, SF and LS. The ratios between different binder parts were varied to obtain a mix design with desirable properties and environmental benefits. In the basic mixture, the amount of FA, GGBFS and SF were determined to obtain the concrete with higher compressive strength (recipe 1–2). FA was used as the base material, making up to 80 wt.% of binder content in various concrete mixtures. This basic concrete mixture was further improved to increase the compressive strength by adding MK and changing the alkaline solution composition and type (recipe 3–14). The effect of MK on strength development was compared with CA. However, to keep the environmental impact comparable, their dosage was different, i.e. CA content was 3 wt.% whereas MK was used up to 15 wt.% of binder content in various concrete recipes.

Moreover, all the recipes were compared with ordinary Portland cement (CEM-I) concrete for environmental impact calculation. Total water to total solid content was varied between 0.22 and 0.30

Table 3 All evaluated concrete mix designs. All the numbers are in kg per 1 m^3 of mixture until specified

Components	CEM-I (Ref)	Geopolymer concrete mixtures													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
CEM-I	330.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
CA	–	–	–	–	15.0	–	–	–	–	–	–	–	–	–	–
FA	–	400.0	280.0	280.0	385.0	385.0	385.0	385.0	350.0	385.0	385.0	375.0	350.0	385.0	375.0
GGBFS	–	50.0	35.0	80.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
SF	–	50.0	35.0	40.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	25.0	50.0	50.0	25.0
MK	240.0	–	–	–	–	15.0	15.0	15.0	50.0	15.0	15.0	50.0	50.0	15.0	50.0
LS	–	–	150.0	100.0	–	–	–	–	–	–	–	–	–	–	–
K-silicate	–	171.0	251.7	171.0	171.0	–	85.5	171.0	171.0	171.0	171.0	150.0	171.0	171.0	171.0
Na-silicate	–	–	–	–	–	114.0	57.0	–	–	–	–	–	–	–	–
KOH	–	–	–	–	–	–	–	–	–	70.6	–	50.0	–	50.0	–
NaOH	–	–	–	–	–	57.0	28.5	–	–	–	–	–	–	–	–
Superplasticiser	13.2	–	–	–	–	–	–	–	10.0	–	10.0	10.0	10.0	10.0	10.0
SRA	–	–	–	–	–	–	–	–	–	–	–	10.0	10.0	10.0	10.0
Air detainer	6.6	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Water (diss)	185.0	70.6	–	77.2	70.6	70.6	70.6	70.6	50.0	–	50.0	–	50.0	–	40.0
Coarse aggregate	800.0	693.6	645.3	617.5	620.5	617.7	618.7	619.7	634.2	643.3	632.5	656.8	625.1	649.2	635.8
Sand	920.0	1040	968.0	926.2	930.8	926.6	928.1	929.5	951.3	964.9	948.7	985.1	937.7	973.7	953.7
Water/Solids	0.36	0.29	0.23	0.30	0.29	0.30	0.29	0.29	0.27	0.22	0.27	0.22	0.28	0.22	0.27
SiO$_2$ (g from solution)		40.0	58.9	40.0	40.0	34.4	37.2	40.0	40.0	40.0	40.0	35.1	40.0	40.0	40.0
K$_2$O (g from solution)		37.1	54.6	37.1	37.1	0.0	18.6	37.1	37.1	60.9	37.1	49.4	37.1	54.0	37.1
Na$_2$O (g from solution)		–	–	–	–	33.5	16.7	–	–	–	–	–	–	–	–
H$_2$O (g from solution)		94.1	138.4	94.1	94.1	102.3	98.2	94.1	94.1	135.8	94.1	112.1	94.1	123.6	94.1

between various mixtures to achieve desirable workability. This was done by changing the amounts of alkaline solution and/or adding water and superplasticiser (SP). The shrinkage in the sample was controlled by the addition of shrinkage-reducing admixture (SRA). Coarse aggregates of size 2 – 8 mm, whereas sand of size 0–4 mm were used. Table 3 also provides the SiO_2, K_2O, Na_2O and H_2O wt.% provided by the alkaline solution in each recipe.

Concrete preparation and testing methods

The compressive strength of concrete prisms of size $4 \times 4 \times 16$ cm^3 was determined after 3, 7, 28 and 90 days with Toni Technik model 2060 from Zwick Roell. Samples were produced by firstly mixing the precursors with the alkaline solution for 90 s in a Hobart mixer, followed by the addition of aggregates and sand and mixing for another 90 s until a homogeneous mixture was obtained. After that, samples were compacted for 120 s on a compaction table and were sealed. The sealed samples were then placed in room with room temperature of 22 ± 1 °C and 65% relative humidity. All samples were demoulded after 24 h of casting and cured in the same room till the testing age. The slump flow of fresh concrete mixtures was determined using a mini-slump cone following the EN 1015–3 [22]. Furthermore, the volume of each mixture was validated in the fresh state.

Life-cycle assessment

To evaluate potential environmental impact reductions of the analysed concrete mix designs, the method of the life-cycle assessment as per ISO 14040 and ISO 14044 is used. The information module of the raw material supply is (information module—A1) considered according to the ISO 14025 and EN 15804 to reflect data harmonisation approaches of the construction sector [23–27].

At this stage of the research, no further relevant life stages were considered. This analysis focuses on the influence of the raw material of the concrete mix designs because the main influence on the environmental impact of concrete mixtures results in conventional cases from the raw material supply [28].

The results refer to the functional unit of 1 m^3 concrete mix. No material flows were excluded based on cut-off criteria. The inputs fly ash, silica fumes and granulated blast furnace slag were considered in the

calculation without any allocation. This approach follows the CEN/TC 51 PCR for cement and building lime. It is applied by major private and public stakeholders in the field of EPDs like the ÖKOBAU-DAT from the German Federal Ministry for Housing, Urban Development and Building as well as from the Dutch Milieu Relevante Product Informartie (MRPI) foundation, which is one the leading data supplier of the Nationale Milieu Database (NMD) from the Netherlands [27, 29, 30].

Environmental cost indicator

The environmental emissions were analysed per the single score method environmental cost indicator (ECI). By monetising environmental costs, the results are aggregated into a so-called single-point score, the environmental cost indicator. The ECI is an appropriate assessment method, especially in the Dutch construction and infrastructure sector. In the Netherlands, its application can be a prerequisite for public tenders. The indicator aims to show the shadow price for the environmental impact of a product or project and to summarise the most significant environmental impact categories as the EN 15804 [26]. For the aggregation, the following impact categories were considered and the weighting from Table 4 is used [31].

Sustainability assessment

In this research, the sustainability approach has been applied to integrate the technical, economic and environmental dimensions of the researched concrete mixtures for three different scenarios of geopolymer based on industrial demands, including S1) Early strength application such as fast pavement restoration to reduce traffic downtime, precast concrete for rapid element manufacturing, high-speed cast-in-place construction, cold-weather construction; S2) Medium strength applications such as floor slab foundation elements; and S3) Late strength such as massive construction, embankment dam and particular application. In addition, the result of the LCA calculation was used for environmental performance; likewise, the economic aspects were calculated for each mixture based on the total cost in Euro per cubic metre (€/m^3) in the reference year 2021.

Furthermore, the Analytical Hierarchy Process (AHP) was applied to weight the technical

Table 4 Weighting for the calculation of the environmental impact indicator (ECI) [31]

Parameter	Unit	Weighting [€/kg eq.]
Abiotic depletion potential (ADP—elements) for non-fossil resources	kg Sb	0.16
Abiotic depletion potential (ADP—fossil) for fossil resources	kg Sb*	0.16
Acidification potential of soil and water (AP)	kg SO_2-eq	4.00
Depletion potential of stratospheric ozone Coat (ODP)	kg CFC-11-eq	30.00
Global warming potential (GWP)	kg CO_2-eq	0.05
Eutrophication potential (EP)	kg PO_4^{3-}-eq	9.00
Formation potential of tropospheric ozone (POCP)	kg C_2H_4-eq	2.00

*If "ADP—fossil" is available in the unit MJ, the conversion factor of 4.81E + 04 kg Sb per MJ can be used

parameters for the mentioned application. AHP is a decision-aiding strategy that allows the decision-maker to organise tangible and intangible components while providing a systematic and transparent answer to challenges [32]. So, a pairwise-comparison questionnaire was distributed among experts, and the weighting of technical parameters was calculated based on the model hierarchy. Because it is proposed to determine the Consistency Ratio (CR) of the AHP matrix [33], the CR was calculated based on Eq. 1.

$$CR = \frac{\left(\frac{\lambda_{\max} - n}{n-1}\right)}{RI} \quad (1)$$

where $\lambda_{\max}$ is the largest eigenvalue of the n × n reciprocal pairwise-comparison matrix and RI is the random consistency index. If the value of CR is smaller or equal to 10%, the inconsistency is acceptable; otherwise, we need to revise the subjective judgment.

In the next step, the Diaz-Balteiro equation has been applied (Eq. 2) [34] to normalise the quantified indicators for technical, economic and environmental performances.

$$\overline{V_i} = \frac{V_i - V_{*i}}{V_i^* - V_{*i}} \quad (2)$$

where V_i is the ith indicator and V_{*i} and V_i^* are the worst and best value of the i_{th} for each indicator to achieve sustainability, respectively.

The technical performance (TP) was then aggregated using Eq. 3 and the weighting obtained from the AHP result.

$$N_{TEC} = \sum_{i=1}^{n} w_i \times \overline{V_i}. \quad (3)$$

Finally, a single sustainability score was calculated based on Eq. 4, and the sustainability sensitivity analysis triangle (S_{SAT}) was created based on the Hofstetter triangle [35, 36] approach to evaluate the best mixture (winner) among the studied concrete recipe for the application as mentioned above (see Fig. 3).

$$\text{Single sustainability score} = N_{ENV} \times w_{ENV} + N_{TEC} \times w_{TEC} + N_{ECO} \times w_{ECO} \quad (4)$$

where N_j is the performance at the level of the dimension $j(ENV, ECO, TEC)$ and w_j is the weight of the dimension j th.

Results and discussion

Technical experimental results

The mini-slump flow results of all the samples are presented in Fig. 4. In most cases, the higher water/binder ratio resulted in higher slump flow. However, adding a superplasticiser and shrinkage-reducing agent (SRA) helped to improve the rheological behaviour. Despite the lower slump flow values, all the mixtures were workable at an industrial scale. The compressive strength results of all the concrete mixtures at various ages are presented in Fig. 5. The compressive strength increased significantly with age for all concrete recipes and ranged between 11.3 and 28.9 MPa at 3 d and between 17.5 and 51.4 MPa at 28 d. The continuous increase in the compressive strength is due to continuing geopolymer reaction and the formation of strength-bearing reaction products. However, the early and late age strength variations indicate a varying geopolymer reaction
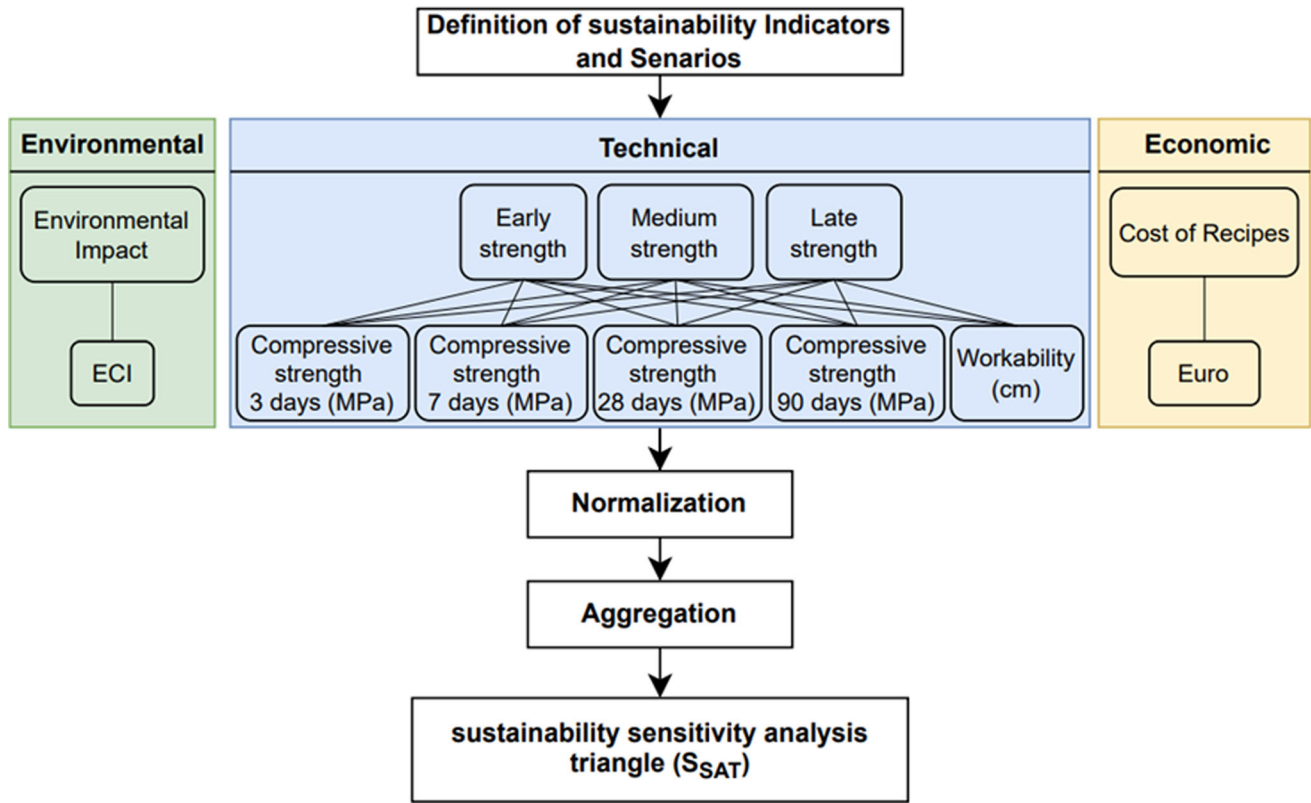
Figure 3 The created framework to select concrete mixtures based on sustainability.

between different recipes. The basic mixture 1 prepared with FA (80 wt.% of binder content), GGBFS (10 wt.% of binder content), SF (10 wt.% of binder content) and potassium silicate solution showed a 3 d compressive strength of 12.2 MPa which increased linearly to 30.4 MPa till 28 d. The addition of limestone (LS) in varying amounts (mixture 2 & 3), varying amounts of potassium silicate solutions and varying content of GGBFS & SF affected the 3 and 28 d compressive strength. For mixture 2, 3 d and 28 d strengths were 15.0 and 24.5 MPa, respectively. Whereas, for mixture 3, these were 11.1 and 17.6 MPa, respectively. Although it is proven in the literature that limestone as a source of $CaCO_3$ is partially reactive in an alkaline medium and promotes the formation of N–C–S–H type phases [37], current results show its reactivity, in this case, is lower than FA, GGBFS and SF. Because of such strength reduction due to the addition of limestone, limestone was not added in further recipes.

To enhance the early strength development, an aluminium source was required. Therefore, as a source of soluble Al_2O_3 partial addition of CA and MK was tested (mixtures 4 & 7). Firstly, to compare

their effect on compressive strength same dosage of both was used, i.e. 3 wt.% of total binder content. The compressive strength results of mixtures 4 & 7 clearly show that adding MK enhances not only the early strength development but also the later strength is improved. The mixture containing 3 wt.% CA of the binder content (mixture 4) exhibited a 3 d strength of 16.7 MPa and 28 d strength of 21.5 MPa, whereas the mixture containing 3 wt.% MK of the binder content (mixture 7) exhibited a 3 d strength of 20.5 MPa and a 28 d strength of 31.1 MPa, thus clearly indicating that the use of MK is beneficial for early and late age strength development. Therefore, further developed recipes consisted of varying proportions of FA, GGSBFS, SF and MK.

In mixtures 5 & 6, sodium and potassium silicate solutions were tested. In mixture 5, only sodium silicate solution was used, whereas, in mixture 6, a combination of half sodium silicate and half potassium silicate solution was used. The potassium silicate solution was used as obtained. However, to achieve a lower silica modulus of sodium silicate solution, a sodium hydroxide solution of 16 mol/kg concentration was added. The compressive strength

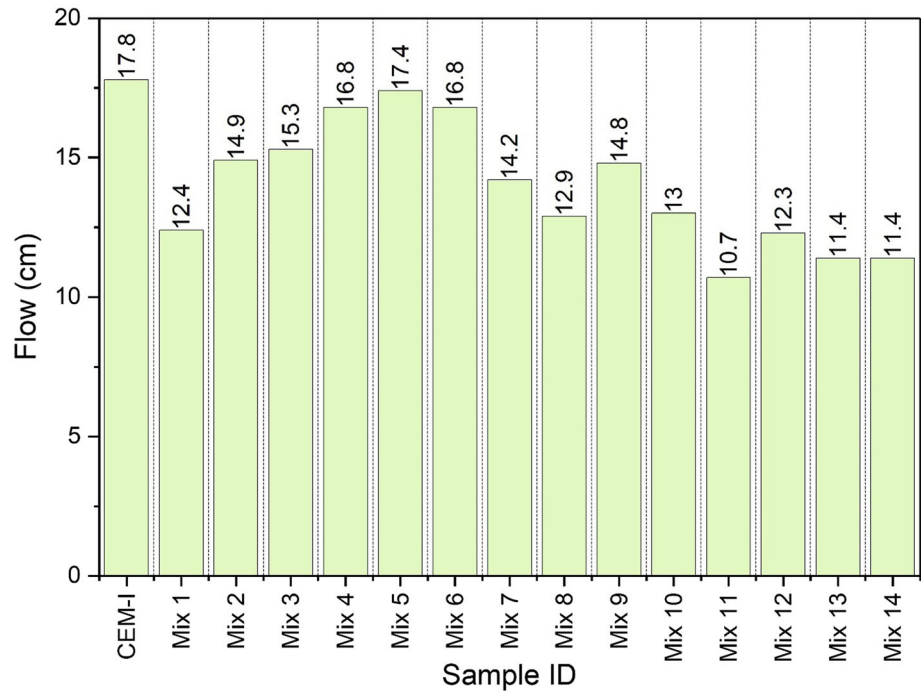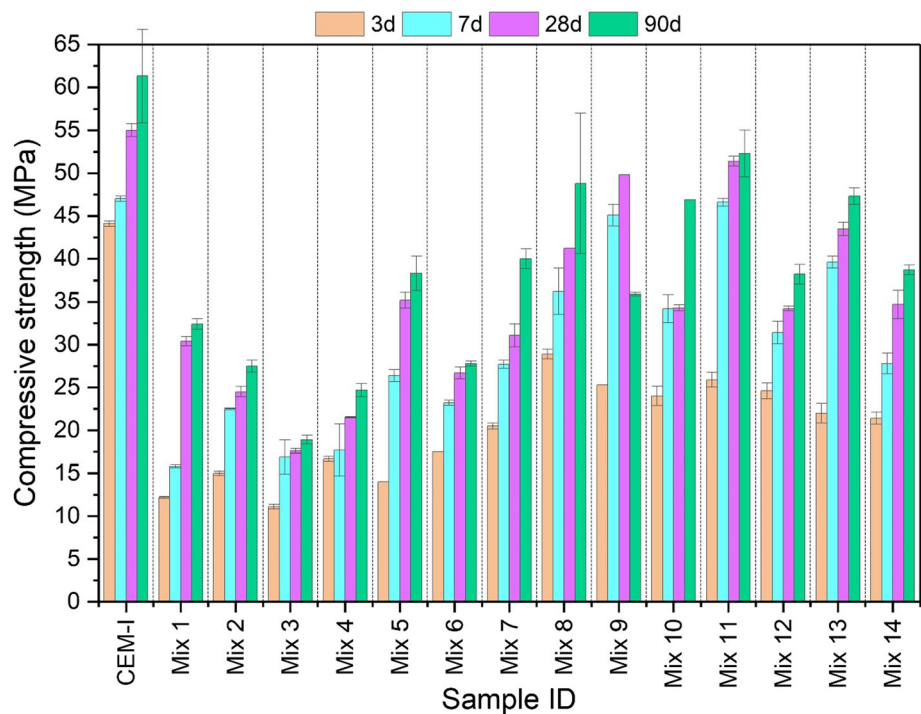**Figure 4** Slump flow of all the tested samples.

Figure 5 Compressive strengths of all concrete mixtures.

results of these samples show that sodium silicate solution alone (mixture 5) is not suitable for achieving higher early strength (3 d compressive strength was 14.0 MPa), whereas a combination of sodium and potassium silicate solution increased the early strength (3 d strength) to 17.5 MPa. However, these strength values are still lower than the mixture 7 (3 d strength of 20.5 MPa), where only potassium silicate solution was used for the same combination. However, the use of only sodium silicate solution (mixture 5) enhanced the 28 d strength compared to mixture 6 (combination of sodium and potassium silicate) and 7
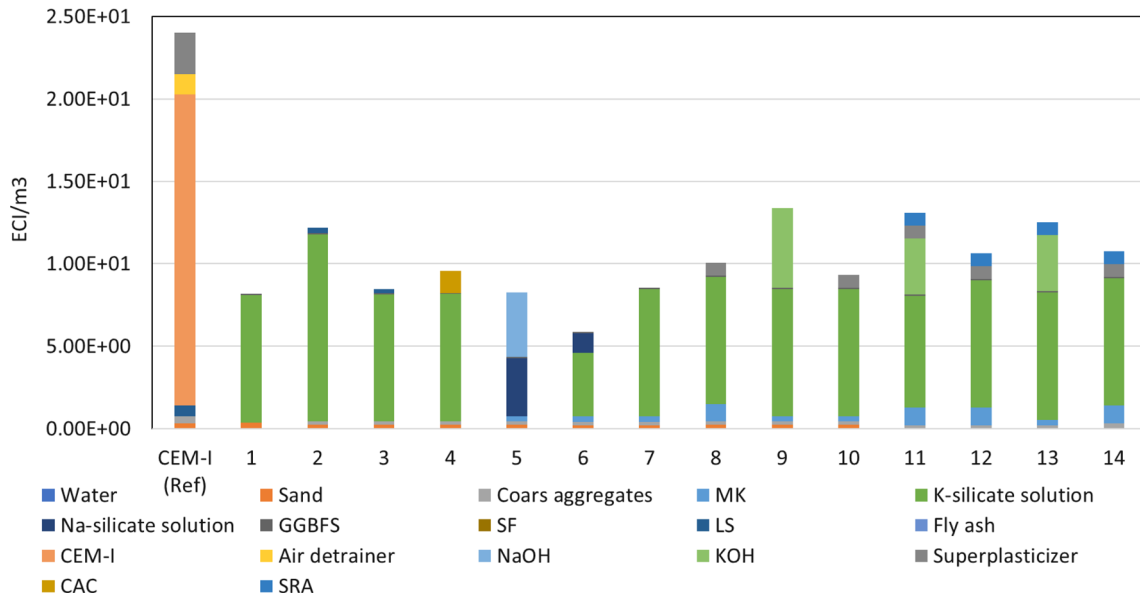
Figure 6 Environmental cost indicator per m³ of all concrete mixtures.

(only potassium silicate). For mixture 5, 28 d strength was 35.2 MPa, whereas, for mixtures 6 and 7, it was 26.7 and 31.2 MPa, respectively.

Summarising these findings shows for these raw materials that potassium silicate solution is better in achieving higher early strengths, whereas sodium silicate solution is better in obtaining higher later age strength. However, early strength is often crucial for industrial applications so that the concrete members can be demoulded earlier and handled efficiently. Therefore, potassium silicate solution was used in further recipes. Compared to mixture 7, mixture 10 was produced with less water and with the addition of a superplasticiser. This addition of superplasticiser helped control workability by reducing the amount of water. Such a reduction in the amount of water resulted in the increase in 3 d strength from 20.5 to 24.0 MPa, thus showing that adding this small amount of superplasticiser was beneficial for strength development because of the water reduction effect.

The mixtures were further developed to optimise the strengths to come closer to the OPC recipe used previously for the same application. In this attempt, MK content was increased in mixture 8 to 10 wt.% of binder content and to compensate for higher water demand, a superplasticiser was used. This recipe showed higher early and late strength (3 d strength of 28.9 MPa, 28 d strength of 41.2 MPa). To accelerate the reaction further, a KOH solution of 16 mol/kg was added instead of water (mixtures 9, 11, 13).

Furthermore, in these recipes, MK and SF content was also varied and superplasticiser and SRA was used to compensate for workability and shrinkage. Mixtures 9, 11 and 13 showed a 3 d strength of 25.3, 25.9 and 22.0 MPa and a 28 d strength of 49.8, 51.4 and 43.5 MPa, respectively. In comparison mixtures 12 and 14 were prepared without KOH solution and exhibited a 3 d strength of 24.6 and 21.4 MPa and a 28 d strength of 34.2 and 38.7 MPa, respectively.

Moreover, 7 and 90 d strengths were also measured for all the samples, which linearly increased in nearly all cases. However, as the focus is on early strength (3 d) and most often referred value in standards (28 d), only these numbers are discussed in this part. However, 7 and 90 d strengths are described in Fig. 5. All in all, the results show that various geopolymer concrete compositions led to different strengths, which can be suitable for various applications. Therefore, as the next step, the question of how a decision about the choice of suitable mixture for a given application leads to the calculation of environmental cost indicator and sustainability in the following sections.

Environmental assessment results

All analysed concrete mixtures were assessed as per the described LCA method and the environmental cost indicator (ECI) was calculated. Figure 6 shows the calculated ECI of the raw material supply

(information module—A1 as per EN 15804 [26]) and the influence of the different raw materials on the various concrete mixtures. In Fig. 6, the first column shows the reference concrete mixture. All concrete mixtures from 1 to 14 show a lower ECI value than the reference concrete mixture. The graphs show that the most significant environmental influence on the reference concrete mixture results from cement CEM-I. The second most significant raw material on the ECI of the reference mixture is the superplasticiser.

Concrete mixtures 1 to 4 and 6 to 14 are mainly determined by the used K-silicate solution. Concrete mixture 4 is the only concrete mixture where CA is added. The influence on the ECI is 14%, although the weight per cent is 3% of binder content, indicating a high specific environmental profile of the CA compared to the other raw materials.

In concrete mixture 5, a combination of NaOH and Na-silicate solution is applied. The influence on the concrete mixture 5 of the Na-silicate solution is 43% and from NaOH is 47%. This mixture shows a reduction potential of 60% in comparison to the reference concrete mixture.

Mixture 6 shows the highest reduction potential compared to the reference concrete mixture. A reduction potential of 72% is analysed under consideration of the raw material supply compared to the reference concrete mixture. The combination of Na-silicate and K-silicate solution is used in concrete mixture 6.

KOH is applied to concrete mixtures 9, 11 and 13. The reduction potential compared to the reference mixture is between 36 and 40%. The influence of the KOH is between 26 and 36%. The primary influence on these concrete mixtures results from the K-silicate solution and shows a contribution of 52 to 62%.

Sustainability assessment

According to the AHP result, Table 5 outlines the significance of technical criteria for each scenario. The expert placed greater emphasis on the compressive strength at three days compared to others at S1. This is primarily since opening the mould at younger ages requires greater compressive strength. It should be noted that the weighting for workability ranges from 7% to 13.8%, which means roughly the same significance in these three circumstances. The CR for all scenarios is below 10%, which is proposed as the maximum for CR. So, the weighting has acceptable inconsistency.

The result of the normalised value for each mixture is presented in Appendix Tables A1–A3. Following an examination of the technical performance of the alternatives, it is possible to get the conclusion that among geopolymers mixtures, Mix 9 for S1 (N_{TEC} = 0.60) and S2 (N_{TEC} = 0.71) and Mix 11 for S3 (N_{TEC} = 0.75) have the most outstanding technical performance overly after CEM-I (Ref) which is obtained the higher score for all scenario (N_{TEC} for S1, S2, S3 = 1). Based on these findings, it is reasonable to conclude that employing a 16 mol/kg KOH solution and increasing MK and SF content in these recipes plus superplasticiser and SRA will result in better behaviour between geopolymers. This is mainly because the superplasticiser and SRA compensated for workability and shrinkage.

From an economic standpoint, the CEM-I (Ref) is the best mixture (N_{ECO} = 1); besides, Mix 3 (N_{ECO} = 0.75) and Mix 1 (N_{ECO} = 0.70) are two geopolymer mixtures that are economically at the top. However, Mix 11 is the worst (N_{ECO} = 0), probably due to the higher cost of potassium hydroxide compared to alternative activators.

At the environmental level, Mix 6 (N_{ENV} = 1) is the best mixture, followed by Mix 1 (N_{ENV} = 0.89) and

Table 5 The order of importance of each technical parameter for each application

Technical Parameters	S1: Early strength (%)	S2: Medium strength (%)	S3: Late strength (%)
Compressive strength 3 days (MPa)	52.6	28.4	6.3
Compressive strength 7 days (MPa)	23.8	42.5	9.6
Compressive strength 28 days (MPa)	8.8	10.1	19.6
Compressive strength 90 days (MPa)	4.0	5.2	57.4
Workability (cm)	10.8	13.8	7.0
Consistency ratio (CR)	5.5	6.7	8.5

Table 6 An example of final score for different mixtures (at ENV = 40%, ECO = 30%, TEC = 30%)

Scenario	CEM-I (Ref)	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Winner
S1	0.600	0.591	0.495	0.595	0.585	0.643	0.692	0.657	0.640	0.445	0.635	0.415	0.529	0.416	0.502	Mix 6
S2	0.600	0.593	0.505	0.602	0.584	0.667	0.700	0.666	0.645	0.477	0.646	0.444	0.533	0.441	0.506	Mix 6
S3	0.600	0.646	0.502	0.586	0.574	0.694	0.687	0.688	0.667	0.431	0.672	0.466	0.536	0.466	0.531	Mix 5
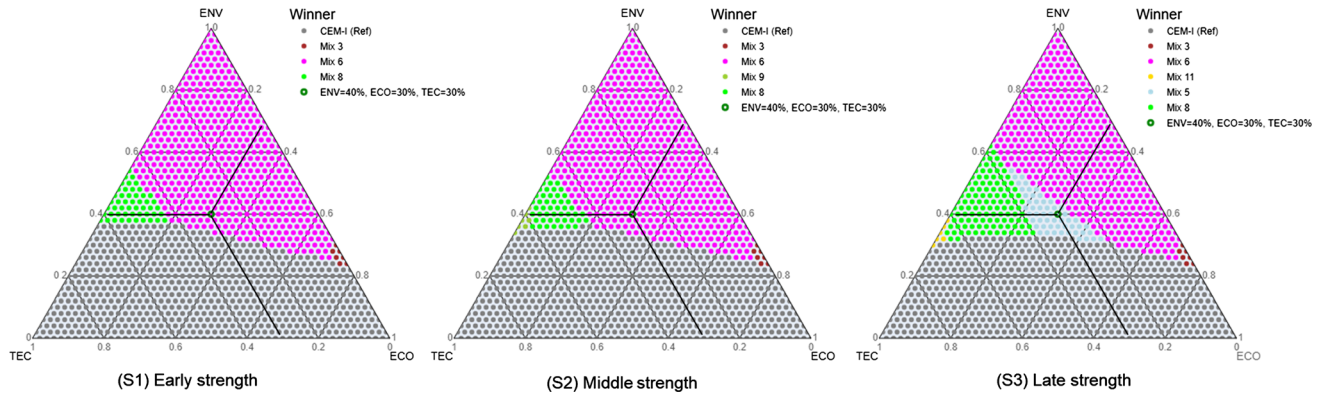
Figure 7 The result of sustainability sensitivity for different scenarios.

Mix 3 (N_{ENV} = 0.86), and Mix 7 (N_{ENV} = 0.87) with no notable change. CEM-I (Ref) is the worse mixture (N_{ENV} = 0) explained in the LCA result.

Finally, each sustainability parameter was subjected to sensitivity analysis to assess the consistency of the results. The weight of one sustainability dimension is represented by each side of the S_{SAT}, and each point on the triangle reflects a weighted average of the three sustainability dimensions. For each point on the triangle, the total sustainability score of all mixtures was determined. As an example, this single sustainability score of Mix 1 is calculated for S1 (at ENV = 40%, ECO = 30%, TEC = 30%) by following Eq. (4) and is as given in (5).

$$\begin{aligned} \text{Single sustainability score} &= 0.89 \times 0.4 + 0.09 \times 0.3 + 0.7 \\ &\quad \times 0.3 \\ &= 0.60 \end{aligned}$$

(5)

The best mixture, as indicated in Table 6, is the one with the highest sustainable score closest to one, which is referred to as a winner. The outcomes of this analysis are depicted in Fig. 7.

Based on the overall analysis, it is possible to conclude that for early strength applications (S1), Mix 7 and Mix 5, and for both middle strength applications (S2) and late strength applications (S3), Mix 5 and Mix 8 are the best and most consistent alternatives among geopolymer mixtures because they performed well for the most weight combinations.

CEM-I (Ref) is only the best answer among the investigated concrete mixtures when the focus is on the economic aspect, with the environmental aspect receiving the least preference (30%). Furthermore, if technical performance (TEC < 1%) is not critical for a certain project, Mix 1 may be more environmentally and economically preferable.

Conclusions

All analysed geopolymer concrete mixtures showed a lower ECI than the reference OPC concrete mixture indicating an environmental impact reduction potential due to replacing the CEM-I binder with a geopolymer binder. From the environmental perspective, following the ECI, concrete mixture 6 with a combination of K-silicate and Na-silicate solutions shows the highest reduction potential. Furthermore, the concrete mixture 5 using Na-silicate and NaOH was identified as the concrete mixture with the

second highest environmental impact reduction potential. A higher early or late age strength depended on the composition of concrete mixtures. The mixtures exhibiting higher strengths inherently contained higher amounts of MK and stronger alkaline solution, thus increasing the ECI. However, their ECI value was still lower than the reference CEM-I. Furthermore, the results of this case study indicate that environmental, technical and economic parameters need to be added to the final assessment to reach towards holistic, sustainable solution or selection of recipes. The weighting scheme is not necessarily based on natural sciences but will inherently depend on economics, environmental and technical preferences for different applications and specific projects. Therefore, S_{SAT} can assist decision-makers in concrete industries select the best recipe for reaching sustainability goals. This paper included an example based on AHP; however, this approach can be used for similar cases of industrial applications.

Acknowledgements

Funding

Declarations

Conflict of interest None.

Supplementary Information: The online version contains supplementary material available at https://doi.org/10.1007/s10853-022-07820-6.

References

[1] International Energy Agency (IEA), World Business Council for Sustainable Development (WBCSD), Cement Sustainability Initiative (CSI) (2018) Technology Roadmap - Low-Carbon Transition in the Cement Industry, France

[2] Editorial, 2021 Concrete needs to lose its colossal carbon footprint Nat https://doi.org/10.1038/d41586-021-02612-5

[3] Monteiro J, Roussanaly S (2022) CCUS scenarios for the cement industry is CO_2 utilization feasible? J CO2 Util. https://doi.org/10.1016/j.jcou.2022.102015

[4] Bilodeau A, Malhotra VM (2000) High-volume fly ash system: concrete solution for sustainable development. ACI Mater J. https://doi.org/10.14359/804

[5] Herrmann A, Koenig A, Dehn F (2017) Structural concrete based on alkali-activated binders: terminology, reaction mechanisms, mix designs and performance. Struct Concr. https://doi.org/10.1002/suco.201700016

[6] Document 52019DC0640, Der europäische Grüne Deal, 2019. European Kommision

[7] Firdous R, Stephan D (2019) Effect of silica modulus on the geopolymerization activity of natural pozzolans. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2019.05.161

[8] Firdous R, Stephan D, Djobo JNY (2018) Natural pozzolan based geopolymers: a review on mechanical, microstructural and durability characteristics. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2018.09.191

[9] Provis JL, van Deventer JSJ (2014) Alkali activated materials, state-of-the-art report, RILEM TC 224-AAM. Springer, Dordrecht, Heidelberg, New York, London

[10] Dontriros S, Nooaek P, Supakata N (2020) Geopolymer bricks from concrete residue and palm oil fuel ash: evaluating physical-mechanical properties, life cycle assessment

and economic feasibility. EnvironmentAsia. https://doi.org/10.14456/EA.2020.14

[11] Colangelo F, Farina I, Travaglioni M, Salzano C, Cioffi R, Petrillo A (2021) Eco-efficient industrial waste recycling for the manufacturing of fibre reinforced innovative geopolymer mortars: Integrated waste management and green product development through LCA. J Clean Prod. https://doi.org/10.1016/j.jclepro.2021.127777

[12] Jiang M, Chen X, Rajabipour F, Hendrickson CT (2014) Comparative life cycle assessment of conventional, glass powder, and alkali-activated slag concrete and mortar. J Infrastruct Syst. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000211

[13] Marinković S, Dragaš J, Ignjatović I, Tošić N (2017) Environmental assessment of green concretes for structural use. J Clean Prod. https://doi.org/10.1016/j.jclepro.2017.04.015

[14] Teh SH, Wiedmann T, Castel A, de Burgh J (2017) Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia. J Clean Prod. https://doi.org/10.1016/j.jclepro.2017.03.122

[15] Abdulkareem M, Havukainen J, Horttanainen M (2019) How environmentally sustainable are fibre reinforced alkali-activated concretes? J Clean Prod. https://doi.org/10.1016/j.jclepro.2019.07.076

[16] Robayo-Salazar R, Mejía-Arcila J, Mejía de Gutiérrez R, Martínez E (2018) Life cycle assessment (LCA) of an alkali-activated binary concrete based on natural volcanic pozzolan: a comparative analysis to OPC concrete. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2018.05.017

[17] Yang K-H, Song J-K, Song K-I (2013) Assessment of CO2 reduction of alkali-activated concrete. J Clean Prod. https://doi.org/10.1016/j.jclepro.2012.08.001

[18] Turner LK, Collins FG (2013) Carbon dioxide equivalent (CO2-e) emissions: a comparison between geopolymer and OPC cement concrete. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2013.01.023

[19] Dahmen J, Kim J, Ouellet-Plamondon CM (2018) Life cycle assessment of emergent masonry blocks. J Clean Prod. https://doi.org/10.1016/j.jclepro.2017.10.044

[20] EN 196–6 (2010) Methods of testing cement – Part 6: Determination of fineness, Brussels. CEN (EN 196–6)

[21] EN 206–1:2000 (2000) Concrete — Part 1: Specification, performance, production and conformity

[22] EN 1015–3 (2007) Methods of test for mortar for masonry: Part 3: Determination of consistence of fresh mortar (by flow table) (EN 1015–3)

[23] ISO 14040 (2006) Environmental management - Life cycle assessment - Principles and framework

[24] ISO 14044 (2006) Environmental management - Life cycle assessment - Requirements and guidelines

[25] ISO 14025 (2006) Environmental labels and declarations — Type III environmental declarations — Principles and procedures

[26] EN 15804:2012+A2:2019 Sustainability of construction works — Environmental Product Declarations — Core rules for the product category of construction products

[27] EN 16908 Cement and building lime – Environmental product declarations – Product category rules complementary to EN 15804; German version EN 16908:2017

[28] (2018) EPD-C 20/25; C 25/30, C 30/37, C 35/45, C 45/55, C 50/60, https://www.beton.org/wissen/nachhaltigkeit/umweltproduktdeklarationen/. InformationsZentrum Beton GmbH

[29] ÖKOBAUDAT (2022) https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=a8640bfd-5ae3-4893-bfe8-d5ab59ec8134&version=20.20.020&stock=OBD_2021_II&lang=de. Federal Ministry for Housing

[30] Nationale Milieu Database (2022) https://data.mrpi.nl/datasetdetail/process.xhtml?uuid=839ab4c9-f857-495f-b533-dac14263bc82&version=04.01.000&stock=PUBLIC&lang=en. Milieu Relevante Product Informartie

[31] SBK (2019) Stichting Bouwkwaliteit (SBK) – Foundation for building quality: Determination method: environmental performance of buildings and civil engineering works

[32] Seraj S, Nikravan M, Ramezanianpour AA, Zendehdel P (2020) Evaluation of the application of municipal solid waste incinerator (MSWI) ash in civil engineering using a sustainability approach. Detritus. https://doi.org/10.31025/2611-4135/2020.13922

[33] Saaty TL (2008) Decision making with the analytic hierarchy process. IJSSCI. https://doi.org/10.1504/IJSSCI.2008.017590

[34] Díaz-Balteiro L, Romero C (2004) In search of a natural systems sustainability index. Ecol Econ. https://doi.org/10.1016/j.ecolecon.2004.02.005

[35] Mateus R, Neiva S, Bragança L, Mendonça P, Macieira M (2013) Sustainability assessment of an innovative lightweight building technology for partition walls – Comparison with conventional technologies. Build Environ. https://doi.org/10.1016/j.buildenv.2013.05.012

[36] Hofstetter P (1998) Perspectives in life cycle impact assessment: a structured approach to combine models of the technosphere, ecosphere, and valuesphere. Springer, Berlin

[37] Firdous R, Hirsch T, Klimm D, Lothenbach B, Stephan D (2021) Reaction of calcium carbonate minerals in sodium silicate solution and its role in alkali-activated systems. Miner Eng. https://doi.org/10.1016/j.mineng.2021.106849