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A TOPSIS and AHP with Spherical Fuzzy Approach for Optimal Selection of Pervious Geopolymer Mix for Heavy Metal Removal

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Geopolymer is an emerging material that is known to have excellent properties. Numerous applications of geopolymer have been reported in various studies, for example, in the construction and building sector, nuclear waste management, and wastewater treatment industry. It gains popularity in the wastewater treatment sector as it can effectively adsorb pollutants (e.g., heavy metals). However, the performance of this material varies depending on different factors such as the type of precursors, mix formulation, process conditions, etc. Moreover, optimal selection should also consider the potential environmental impact and safety to the general public before field application. The utilization of coal fly ash and other potential material was investigated to develop a pervious geopolymer. In this study, selection of optimized geopolymer mix for heavy metal removal using TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and AHP (Analytic Hierarchy Process) with a spherical fuzzy approach was employed. An illustrative case study is presented for the proposed decision modeling technique in optimally selecting pervious geopolymer mix.

1. Introduction

In recent years, the demand for conventional concrete has increased due to rapid industrialization. Concrete is composed of cement, coarse aggregates, fine aggregates, and water. With the surge in the demand for concrete, an equivalent threat to the environment awaits. The construction industry, being one of the consumers of concrete, is compelled to look for an alternative material that would help mitigate the use of cement as a primary material. An interesting new and eco-friendly found material, geopolymer, has been gaining attention due to its excellent properties. This material has often been looked at as an alternative to cement. A study conducted by Dollente et al. (2021) showed that the geopolymer concrete has a global warming potential of 32 % less than the traditional concrete made of cement. This indicates that the use of this material in the construction industry and other sectors such as wastewater treatment for heavy metal removal is promising. Pervious geopolymer is made from a precursor, alkali activator, and coarse aggregates. The potential precursor for pervious geopolymer can be a waste material composed of aluminosilicate. The type of precursors, mix formulation, and process conditions may greatly affect the properties of the pervious geopolymer. Moreover, safety and risk to the environment before field application must also be taken into consideration. Hence, it is imperative to determine the optimal mix proportion and other factors that may affect when the product is deployed.

To thoroughly evaluate the pervious geopolymer considering the qualitative and quantitative factors such as properties, safety to the public, and risk to the environment, this study aims to employ TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and AHP (Analytic Hierarchy Process) with spherical fuzzy technique. Kutlu Gündoğdu and Kahraman (2019a) have studied both approaches with spherical fuzzy technique independently. Meanwhile, the modified approach presented in this study strengthens the results of the decision-makers in selecting the optimal mix proportion in developing a pervious geopolymer as it addresses the possible uncertainties in making selections by combining the two approaches- TOPSIS and AHP with spherical fuzzy technique extension.

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2. Materials and method

The figure below illustrates the overview of the study. It is divided into four parts- Development of pervious geopolymer, evaluation of criteria, calculation of weighted matrix, and selection of pervious geopolymer mix.

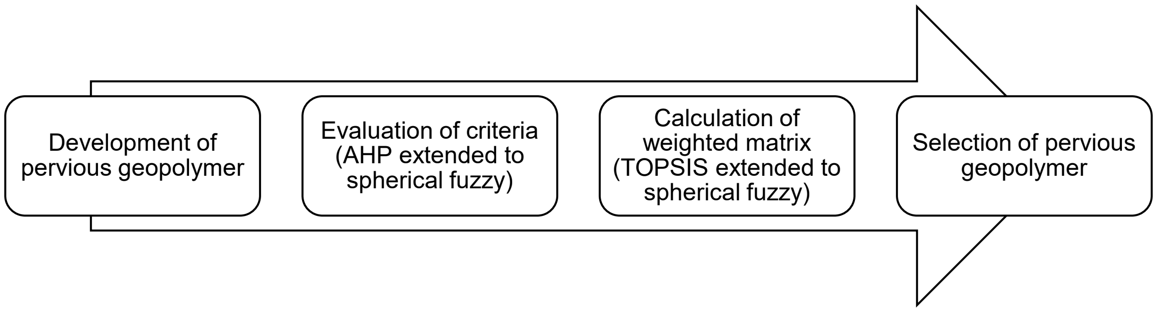

Figure 1: Overview of the methodology

The experimentation was done using various mixes of precursor and activator to develop geopolymer. After gathering the data, an assessment of the optimal mix design was done by employing techniques of AHP and TOPSIS extended spherical fuzzy. The spherical fuzzy set integration accounts for the fuzziness and ambiguity in judgments made in evaluating the linguistic scale in AHP and in rating the alternatives using TOPSIS (Kutlu Gündoğdu and Kahraman, 2019a). The criteria weights for the linguistic scale were calculated using AHP pairwise comparison while the ranking of alternatives was based on TOPSIS.

2.1 Materials

Coal fly ash (CFA) was collected from a coal-fired power plant in the central region of Luzon, Philippines, and was used as received. Coarse aggregates (CA) used were gravel and were purchased from Rizal, Luzon. Chemical reagents such as sodium hydroxide micro-pearls with 99 % purity, sodium silicate with a composition 44 % SiO_2, and nickel sulfate hexahydrate with 98 % $NiSO_4.6H_2O$ were used in the study.

2.2 Development of pervious geopolymer

Pervious geopolymer concrete samples were prepared in accordance with the following formulations as shown in Table 1. Alkali activator (AA) is composed of $NaSiO_3$ / NaOH at a ratio of 2.5:1 (Tho-In et al., 2012). The response variables are compressive strength and heavy metal removal.

Table 1: Pervious geopolymer mix proportion

Mix Design Code	CFA:CA ratio	AA:CFA ratio	NaOH Concentration (M)
Mix No. 1	1:6	0.65:1	15 M
Mix No. 2	1:9	0.65:1	15 M
Mix No. 3	1:9	0.65:1	10 M
Mix No. 4	1:6	0.45:1	10 M
Mix No. 5	1:9	0.45:1	10 M

Initially, CFA and AA were mixed in a mechanical mixer for 5 minutes. Then, CA was added and mixed for another 5 mins. The mixture was then poured into cylinder molds and allowed to rest for 30 mins. The molded samples were wrapped in a zip bag and were cured for 24 h at 80 °C in the oven. After oven curing, the samples were demolded and cured for 28 d at ambient environment. The compressive strength of pervious geopolymer was tested using Universal Testing Machine. For heavy metal removal efficiency, the concentration of nickel in the solution before and after passing through the pervious geopolymer was measured using Atomic Absorption Spectroscopy.

2.3 Evaluation of criteria based on AHP and spherical fuzzy approach

The diagram shown in Figure 2 illustrates the criteria considered such as toxicity (C1), life cycle analysis (LCA) (C2), compressive strength (C3), and removal efficiency (C4). The AHP integrated with spherical fuzzy set was used to evaluate the weights of each criterion. The details and the description of the criteria and the alternative considered in the study are shown in Table 2.

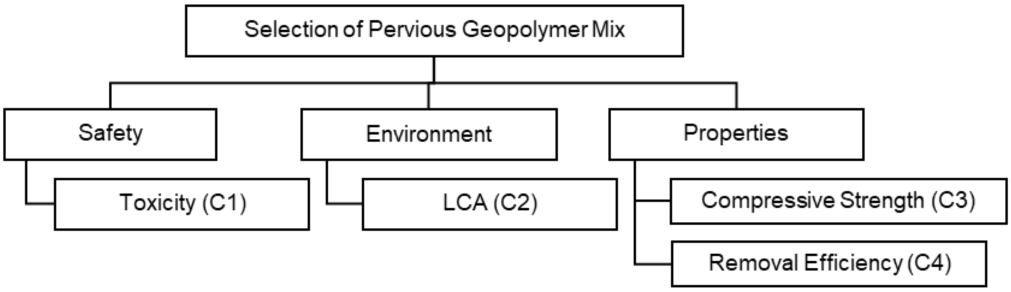

Figure 2: Criteria used in selecting the optimal mix formulation

Table 2: Description of criteria and alternatives

Cluster	Element	Description
Goal	Goal	To evaluate and select the optimal mix formulation of pervious geopolymer
Criteria	Safety – Toxicity*	The chance of harmful effects on human during preparation and deployment and is measured qualitatively
	Environment – LCA*	The potential impact on the environment in terms of the material used and related logistics. It is estimated to be measured qualitatively
	Properties – Compressive Strength	Obtained from the experimental result after 28 d of curing
	Properties – Removal Efficiency	Obtained from the experimental result after passing through the column setup
Alternatives	Mix Design 1	In reference to Table 1 formulation
	Mix Design 2	In reference to Table 1 formulation
	Mix Design 3	In reference to Table 1 formulation
	Mix Design 4	In reference to Table 1 formulation
	Mix Design 5	In reference to Table 1 formulation

The proposed AHP extended to spherical fuzzy starts by populating the matrix with the value judgment on linguistic scale to describe the relative importance of one criterion over the other. A pairwise comparison was performed as shown in Table 3. Each scale has an equivalent spherical fuzzy number that was used to calculate the weighted and normalized weight of criteria (Kutlu Gündoğdu and Kahraman, 2019b).

Table 3: Linguistic scale with spherical fuzzy set (AHP integrated)

Scale	Code	Spherical Fuzzy Number [μ, v, π]	Score index
Very Strongly (More Important)	VSM	[0.9, 0.1, 0.1]	8
Strongly/Highly (More Important)	STM	[0.8, 0.2, 0.2]	5
Moderately (More Important)	MM	[0.7, 0.3, 0.3]	3
Slightly (More Important)	SM	[0.6, 0.4, 0.4]	2
About Equal	AE	[0.5, 0.5, 0.5]	1
Slightly (Less Important)	SL	[0.4, 0.6, 0.4]	1/2
Moderately (Less Important)	ML	[0.3, 0.7, 0.3]	1/3
Strongly/Highly (Less Important)	STL	[0.2, 0.8, 0.2]	1/5
Very Strongly (Less Important)	VSL	[0.1, 0.9, 0.1]	1/8

2.4 Calculation of weighted normalized decision matrix based on TOPSIS and spherical fuzzy technique

On ranking the alternatives using TOPSIS, populating the decision matrix with alternatives and criteria with scores is the first step. The scores can be either quantitative or qualitative assessments. In this study, C3 and C4 (quantitative) values were obtained using the experiment and while C1 and C2 (qualitative) were evaluated using the linguistic scale shown in Table 4.

Table 4: Linguistic scale with spherical fuzzy set (TOPSIS integrated)

Scale	Code	Spherical Fuzzy Number [μ, v, π]	Rating
Ideal Best/Perfect	IB	[1.0, 0.0, 0.0]	1.00
Excellent	EX	[0.9, 0.1, 0.1]	0.73
Very good	VG	[0.8, 0.2, 0.25]	0.48
Good	GD	[0.7, 0.3, 0.35]	0.32
Slightly good/Above satisfactory	AS	[0.6, 0.4, 0.4]	0.22
Moderate/Satisfactory	S	[0.5, 0.5, 0.5]	0.18
Slightly bad/Below Satisfactory	BS	[0.4, 0.6, 0.4]	0.10
Bad	BD	[0.3, 0.7, 0.35]	0.06
Very bad	VB	[0.2, 0.8, 0.25]	0.03
Worst	WO	[0.1, 0.9, 0.1]	0.01
Ideal Worst	IW	[0.0, 1.0, 0.0]	0.00

The judgments made on qualitative data were transformed into a numerical score. The weighted normalized decision matrix was then evaluated based on TOPSIS and spherical fuzzy numbers using Eq(1) and Eq(2).

$$\bar{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}} \quad (1)$$

$$V_{ij} = \bar{X}_{ij} \times W_j \quad (2)$$

Then, the positive ideal and negative ideal solutions are identified based on the criterion- if benefit or cost type. For the cost type, the lower the score, the better the alternative concerning that criterion. Meanwhile, for the benefit type, the higher the score, the better the alternative concerning that criterion. A measure of the separation via Euclidian distance from the positive ideal and negative ideal solution is calculated using Eq(3) and Eq(4).

$$S_i^+ = \left[\sum_{i=1}^{n} (V_{ij} - V_j^+)^2\right]^{0.5} \quad (3)$$

$$S_i^- = \left[\sum_{i=1}^{n} (V_{ij} - V_j^-)^2\right]^{0.5} \quad (4)$$

Lastly, the performance score which was based on the relative closeness to the ideal solution was calculated using Eq(5) and the ranking of alternatives follows.

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (5)$$

3. Results and discussion

3.1 Properties of pervious geopolymer

Table 5 shows the measured compressive strength of pervious geopolymer which ranges from 1.02 MPa – 2.09 MPa and the recorded removal efficiency which ranges from 96.0 – 98.1 %.

Table 5: Pervious geopolymer mix proportion

Mix Design Code	Compressive Strength (MPa) (C3)	Removal Efficiency (%) (C4)
Mix No. 1	2.09	96.7
Mix No. 2	1.13	96.8
Mix No. 3	1.02	96.0
Mix No. 4	1.25	98.1
Mix No. 5	1.20	98.1

The removal efficiency was observed to be high for all runs. The possible mechanism of nickel removal is due to precipitation. At higher pH, nickel can precipitate as nickel hydroxide ($Ni(OH)_2$). Considering the environment of pervious geopolymer which is known to be alkaline, this phenomenon may have occurred. Moreover, a study by Escudero et al. (2017) showed that nickel precipitates completely at a pH of 11. This further supports the results of this study. On the other hand, the compressive strength has been observed to be low for all samples. The size of the coarse aggregate may have been a factor that can be considered in future works. These two properties of pervious geopolymer were used in the succeeding analysis for the optimal selection of mix formulation using TOPSIS and AHP integrated with spherical fuzzy numbers.

3.2 Criteria weights based on AHP and spherical fuzzy approach

Analytic Hierarchy Process is a multi-criteria decision analysis tool introduced by Saaty (1987) wherein both quantitative and qualitative factors are considered in modeling the complexity of the decision problem hierarchically (goal, criteria, and alternatives) to derive weights or priorities using pairwise comparison. Another approach to integrating with this tool is the use of a spherical fuzzy set number to quantify the qualitative data. Table 6 shows the pairwise comparison of each criterion using the linguistic scale with numerical value as tabulated in Table 3. The transformed data with the equivalent fuzzy set and the synthesized criterion with the derived weight is shown in Table 7.

Table 6: Pairwise comparison matrix for criteria

	Toxicity (C1)	LCA (C2)	Compressive Strength (C3)	Removal Efficieny (C4)
Toxicity (C1)	AE	MM	STM	MM
LCA (C2)		AE	AE	AE
Compressive Strength (C3)			AE	AE
Removal Efficiency (C4)				AE

Table 7: Synthesized criteria weights

	μ	v	π	Normalized
Toxicity	4.106	0.031	20.187	0.367
LCA	1.413	0.026	11.775	0.214
Compressive Strength	1.347	0.020	11.520	0.209
Removal Efficiency	1.347	0.020	11.520	0.209

3.3 Decision Matrix Weights based on TOPSIS and spherical fuzzy technique

TOPSIS approach integrated with spherical set was also used to evaluate and rank the mix formulation based on the desired criteria. Table 8 shows the summary of the decision matrix. This provides us an overview of the mix formulation with the corresponding scores derived from an experimental and qualitative estimation of scores.

Table 8: Summary of decision matrix

Mix Design	Toxicity*	LCA*	Compressive Strength (MPa)	Removal Efficiency (% Removal)
Mix No. 1	GD	AS	2.09	96.7
Mix No. 2	VG	VG	1.13	96.8
Mix No. 3	EX	VG	1.02	96.0
Mix No. 4	S	S	1.25	98.1
Mix No. 5	AS	EX	1.20	98.1

Tables 9, 10, and 11 showed the results of calculation steps for each alternative. Lastly, the resulted rank is shown in Table 12. The final ranking showed that the optimal mix formulation of pervious geopolymer based on the criteria presented is mix design no. 5 which is composed of CFA / CA ratio of 1:9, AA / CFA ratio of 0.45:1, and sodium hydroxide concentration of 10M.

Table 9: Transformation of qualitative data with spherical scoring function

Mix Design	Toxicity*	LCA*	Compressive Strength (MPa)	Removal Efficiency (% Removal)
Mix No. 1	0.32	0.22	2.09	96.7
Mix No. 2	0.48	0.48	1.13	96.8
Mix No. 3	0.73	0.48	1.02	96.0
Mix No. 4	0.18	0.18	1.25	98.1
Mix No. 5	0.22	0.73	1.20	98.1

Table 10: Fuzzified and normalized decision matrix

Mix Design	Toxicity*	LCA*	Compressive Strength	Removal Efficiency
Mix No. 1	0.33	0.21	0.67	0.45
Mix No. 2	0.49	0.46	0.36	0.45
Mix No. 3	0.75	0.46	0.33	0.44
Mix No. 4	0.19	0.17	0.40	0.45
Mix No. 5	0.22	0.70	0.39	0.45

Table 11: Weighted normalized decision matrix

Mix Design	Toxicity*	LCA*	Compressive Strength	Removal Efficiency	S_i^+	S_i^-	P_i
Weights	0.12	0.04	0.14	0.09			
Mix No. 1	0.18	0.10	0.08	0.09	0.118	0.171	0.591
Mix No. 2	0.28	0.10	0.07	0.09	0.140	0.113	0.446
Mix No. 3	0.07	0.04	0.08	0.09	0.226	0.062	0.216
Mix No. 4	0.08	0.15	0.08	0.09	0.127	0.208	0.621
Mix No. 5	0.12	0.04	0.14	0.09	0.061	0.225	0.786

Table 12: Resulted rank for optimal selection

Mix Design	CFA/CA	AA / CFA	Sodium Hydroxide Concentration	Rank
Mix No. 1	1/6	0.65	15 M	3
Mix No. 2	1/9	0.65	15 M	4
Mix No. 3	1/9	0.65	10 M	5
Mix No. 4	1/6	0.45	10 M	2
Mix No. 5	1/9	0.45	10 M	1

4. Conclusions

Pervious geopolymer developed in this study uses coal fly ash as precursor. The properties of geopolymer obtained from the experimental results are compressive strength and removal efficiency. Together with this data, qualitative factors such as toxicity and life cycle assessment have also been considered. These factors were used to select the optimal mix formulation of pervious geopolymer. Considering quantitative and qualitative data, aggregation of these data has been made possible because of the new technique that was integrated into this study - TOPSIS and AHP integrated with spherical fuzzy set. This shows that this approach is a straightforward tool that can be used in multicriteria decision-making that aims to minimize uncertainties in making selections. Of the five alternatives, the mix design that has been favored based on the set criteria was the mix design no. 5 with a composition CFA/CA ratio of 1:9, AA/CFA ratio of 0.45:1, and 10 M sodium hydroxide concentration.

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