



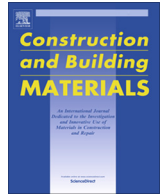
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Moving towards resource conservation by automated prioritization of concrete mix design

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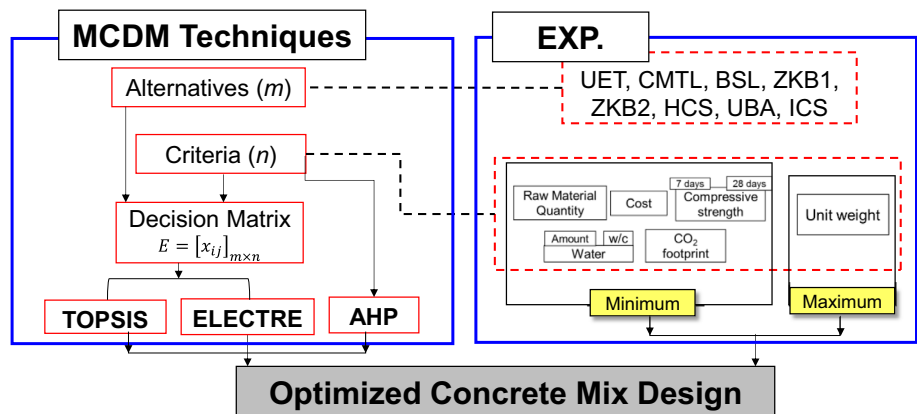
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HIGHLIGHTS

- Prioritization of concrete mix by integrating resource conservation and environmental performance.
- Quantification of raw materials, cost, CO₂ footprints and strength of eight mix designs.
- Optimal selection of concrete mix design by following eight criteria by MCDM techniques.

GRAPHICAL ABSTRACT



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ABSTRACT

Selection of an optimal concrete mix design by integrating resource conservation and CO₂ footprint was performed in this study. Eight concrete mix designs were obtained from contractors, laboratories, and manufacturers as alternatives. Eight criteria by considering; natural materials utilization, economy, strength, and environmental impact, were quantified against eight alternatives. Three types of multi criteria decision making (MCDM) techniques were used for the prioritization of mix designs by assigning equal as well as different preference to the criteria. The resulted mix exhibited a balance between required performance, economy, resource conservation and CO₂ footprint. The profit by using prioritized mix design was evaluated through a case study of a mega project of a developing country. Results obtained by the MCDM techniques were evaluated for varying stakeholder preferences. The results depicted the effectiveness of MCDM techniques in complex decision-making scenarios and close correspondence was observed. This study can be used in the construction industry to select the most suitable concrete mix design by varying the preference of criteria according to a wide range of conflicting requirements of stakeholders and industry.

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1. Introduction

The infrastructure development is an indispensable need of the society due to rapid industrialization and increase in population. The construction industry is directly linked with the infrastructure development and it consumes around 44% of the natural resources of this planet [1]. Generally, concrete is seen as a multipurpose/all-around material being the prime natural resource for infrastructure development. Concrete, also being a heterogeneous material, utilizes several of our natural resources. Therefore, there is an ever-growing need to investigate and devise new techniques in order to optimize concrete mix design, reduce the natural resources consumption, minimize wastage and make the process of concrete design and construction efficient.

Over the period of time, researches have been striving to produce low cost, low density, low thermal conductivity concrete with good mechanical properties [2]. Economy and mechanical properties have always been the areas of interest for researchers since the past few decades. Owing to increasing awareness about climate change and its adverse impacts on the environment the importance of resource conservation and ecofriendly processes are on the rise within the construction industry. Now is the right time to take decisive initiatives towards optimizing mix design by taking into account its environmental impact to reduce the reckless use of natural resources. Over the past few years, there has been a growing understanding of the detrimental effects of the construction industry on the environment. The construction industry, along with material industry is directly posing threats to the environment by the depletion of natural raw materials, emission of greenhouse gases and high energy consumption in extraction, transportation, construction, operation, maintenance and demolition [3,4]. The construction industry is also a major contributor in the emission of greenhouse gases both in European Union (EU) (16%) and in other countries (5–40%) [5]. An estimated 5.7 billion tons of CO₂ was emitted by the construction sector in 2009 which was 23% of the total global economic activities [6]. Building technologists now agree that global development should run parallel with the application of methodologies, technologies and initiatives that are less resource intensive and less environmental damaging while maintaining profit. United Nations emphasizes the conservation and sustainable use of natural resources through the achievement of sustainable development goals by the year 2030. It emphasizes the efficiency of resource usage and switching to clean and environmentally safe technologies and processes. Construction industry demands newer technologies, a reduce in natural resources approach, use of advance and modified materials, reuse and recycling technologies and other strategies to lessen the use of natural raw materials. On account of huge CO₂ emissions and ongoing usage of depleting natural resources in concrete production, it has huge potential for the implementation of resource conservation strategies.

Concrete is the most widely used construction material as well as the second most consumed substance after water. It is estimated that almost 25 billion tons of concrete are produced every year [7]. Concrete accounts for about 50% of the total materials manufactured around the world [8]. Cement being the key ingredient of concrete has shown a remarkable increase in its production from 1.8 billion ton to 3.7 billion ton from 2002 to 2013 [9–11]. Concrete consumption in the construction industry drives the use of raw materials which influences the depletion of natural resources. It has adverse effects on environment as a huge amount of CO₂ is emitted during production of raw materials for concrete, primarily through cement production processes [4,12]. About 65% of CO₂ emissions occur from the raw materials, particularly limestone used in the production of cement clinker [13]. An increase in

construction and development activities in the developing countries has led to the annual growth rate of 4% for cement production [14]. The cement industry is responsible for about 5–8% of the total CO₂ emission in the environment [15]. This CO₂ is added into the natural environment through the processes of calcination of limestone and subsequent combustion of the clinker. Such a scenario resulted in global warming which is a serious threat to human beings and the green environment. As the high amounts of CO₂ act as a blanket and thus trap heat in the atmosphere thus lead towards an increase in temperature. A research work was also carried out for proportioning concrete ingredients for desired strength and reduced global warming potential [16].

The cost of construction works is directly influenced by the materials used in the construction process. For instance, a comparative study on the construction of reinforced concrete (RC), steel and composite structures revealed that cost of composite steel structure and steel structure were 41% and 38% higher than that of RC structures [17]. Being a relatively economical material, concrete construction outruns other construction works in developing countries. Cement is the most expensive ingredient used in concrete production with the highest adverse impacts on the environment. Furthermore, the cost of cement is on a continuous rise to meet the increasingly growing demand of the construction industry. According to building construction statistics, the price of cement rose from 95 to 113 USD per metric ton from 2013 to 2017 in the United States [18]. Therefore, a need of finding ways to cut down the cost of cement arose. Cost of concrete can be reduced by; cutting down the cement content by replacement or varying the concrete mix proportions, which in turn will also reduce its environmental impacts. An investigation of concrete by varying constituents and their combinations has been done, to analyze cost effectiveness [19]. However, the cost alone is not the sole parameter to select and optimize concrete mix design.

In normal concrete, cement acts as a binder and controls the strength of concrete apart from the coarse aggregate. Another important parameter is the water-to-cement (w/c) ratio which affects various fresh and hardened properties of concrete. The w/c ratio of 0.45 to 0.60 is usually used in normal concrete in developing countries. Results also showed that an increased cement content favors compressive strength, consequently, leads to decreased aggregate content and corresponding marginal reduction in the density of concrete mix [20]. Whereas, low density of concrete degrades the durability of concrete by increasing its porosity and making it more susceptible to the adverse effects of the environment. Water; a natural resource, is depleting at alarming rate. In the wake of water scarcity, United Nations' sixth sustainable development goal emphasizes the immediate need to minimize wastage of water because 40% of the world's population is affected by water scarcity. It's our responsibility to conserve and ensure water management for our future generations. Water conservation cannot be achieved without reducing its demand in domestic and construction sector and without its efficient usage in concrete production. Therefore, selection of mix proportion; the amount of cement, water and aggregates is a balanced approach which is vital for its performance and durability.

Concrete is designed by following some standard practices and codes to attain the required workability, compressive strength and long-term durability [21,22]. However, the conservation of natural resources and CO₂ footprint due to the production and consumption of concrete, are mostly ignored. Selection of suitable mix design is prioritized in variable ways by different stakeholders. Amount of concrete ingredients variably customized by different stakeholders are critical to the performance of these structures. They also affect the project cost as well as influence the environment. Consultants and contractors mostly prefer an economic

concrete mix with project-specific compressive strength and durability while ignoring its environmental impacts. Various researchers have suggested different approaches to minimize the adverse impacts on the environment including nano-engineering, cleaner technologies [9] and by use of alternative materials in concrete production [23–26]. Efficient use of materials with minimum waste generation is also closely related to resource conservation [27]. Industries and researchers are moving towards the reduce, reuse and recycle strategies to minimize waste and efficiently use natural resources. The conservation of cement, water, coarse and fine aggregates and reduction of carbon dioxide emission during concrete construction play a vital role to achieve global resource conservation and environmental sustainability. Therefore, it is imperative to incorporate these important factors during a selection of mix design.

In a nutshell, parameters such as compressive strength, durability, and economy most commonly form the basis of selection of appropriate mix design. Whereas, the parameters of resource conservation and environmental impact are mostly neglected while selection of an optimized mix. The selection of optimized concrete mix design complying the aspects of resource conservation, economy, environmental impact, and structural performance is a multi-criteria decision making (MCDM) problem. Due to time restriction in infrastructure projects, it is an unmanageable as well as an arduous task to recalculate and test all the alternatives and select an optimum mix design. Therefore, analytical analysis incorporating various alternatives and parameters with customized prioritization as desired by the stakeholders would help in saving time and cost. Such analytical analysis would also avoid unnecessary objections in complex decision-making processes. MCDM analysis is a useful tool to assess construction processes and can be applied to make quick and accurate decisions in the construction industry [28]. Such techniques have been applied in construction and risk management, supplier and contractor selection as well as material selection in the construction industry [29–32]. In this aspect, there are many methods such as; Analytical Hierarchy Process (AHP), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Elimination Et Choice Translating Reality (ELECTRE) for solving the selection problems [28].

Analytical techniques such as TOPSIS and PROMETHEE method are directly used to prioritize the suitable alternative based on selected criteria such as compressive strength. Particularly, results obtained through TOPSIS are summarized in the form of positive and negative ideal solutions. On the other hand, AHP and ELECTRE prioritize alternatives based on pairwise comparison. In these methods, all the alternatives are pairwise compared with multiple selected criteria altogether. Decisions based on these analyses cannot be otherwise quantified and are difficult to handle.

This study is an attempt to automate the strenuous process of selection of optimal mix design by using MCDM analytical techniques. Various factors including resource conservation, economy, environmental impact and structural performance, which may vary according to the demand of the project and stakeholders, are evaluated and compared using MCDM methods. Varying preferences were assigned to the selected criteria according to the stakeholder requirements. Decision matrix was formulated by using eight concrete mix designs as alternatives. Three types of MCDM techniques; TOPSIS, ELECTRE, and AHP, were applied to prioritize the concrete mix and to achieve a balanced mix design, having desired performance, resource conservation and least CO₂ footprint. The aim of the research is to finally reach a mix design that besides being most economical solution, will satisfy the performance requirement as well as will impart minimum impact to environment.

1.1. Significance of the study

This research finds its applicability from the fact that the various conflicting requirements of the stakeholders from construction and concrete production industry can be modeled in this work. It can offer a great benefit to help all the stakeholders (consultant, contractor, client, developers, construction managers, and civil engineers) to make more informed decisions in complex field scenarios. This is made by using MCDM techniques, incorporating/fulfilling the factors of optimizing performance, durability, cost, resource conservation and environmental sustainability in less time and with minimum effort. Models based on this study encompass requirements and priorities of various stakeholders. For instance, each stakeholder might have different criteria with reference to importance factor while selecting a suitable mix design. This can be easily altered by varying weight functions for various selected criteria. Hence, the preference for economy by clients and contractors, the preference of strength and durability by consultants and the preference of resource conservation and environmental sustainability by the developers can be incorporated to find an optimal mix design. These MCDM techniques are fast and can be applied to any part/aspect or process in the concrete construction industry at the initial stages of the project. It will reduce the time required for the selection of materials, equipment, machinery, process etc. as well as avoid the loss of money if an inappropriate decision is made.

2. Methodology

2.1. Mix design

The concrete cylindrical compressive strength of 28 MPa after 28 days, which is mostly used in public sector projects in developing countries, was set as a target and eight concrete mixtures were used as alternatives for selection of the optimized mix. Three mix designs were obtained from the well-established laboratories including the laboratory belonging to the author's University of Engineering and Technology, Lahore, Pakistan. Three mix designs were obtained by well-reputed contractors which have done several mega concrete projects in Pakistan. One mix design was obtained by the commercial supplier of concrete as well as one mix design which had already been used in one mega project in Lahore, Pakistan. The details of design sources along with the acronyms used in this study are mentioned in Table 1. All concrete mix designs contained similar cement (ASTM Type-I), locally sourced sand and coarse aggregate, whereas it contained different types of admixtures. Tests were performed to evaluate the physical properties according to ASTM guidelines: [33] (for aggregate), [34] (for cement), [21] (concrete mix design), [35] (for admixture), [36] (Petrographic tests for aggregates). All mix designs qualified the 7 and 28 days target compressive strength requirements. The properties of fine aggregate and admixtures are mentioned in Table 1, properties of coarse aggregate are mentioned in Table 2. The mix proportion of all constituents of eight mixtures are mentioned in Table 3.

2.2. Identification of criteria for prioritization

Selection criteria for determining the optimal mix design is often a prioritized approach in a decision-making process. Preferences are dependent on the requirement of stakeholders; client, consultant, contractor, commercial laboratory and concrete manufacturer. Mostly, cost and performance are given more importance and resource conservation and environmental impacts are ignored. Thus, selection of criteria must be followed by a rigorous process,

Table 1

Physical properties of fine aggregate, types of admixture and water-cement ratio of all types of mixtures.

Sr. No	Design Sources	Lawrence pur Sand				Admixture name	Chemical Base	Acronyms
		FM ¹	Gs ²	Abs. ³	L.D ⁴			
1	Mix 1	2.49	2.7	1.22	1394	SIKA 512	Naphthalene	UET
2	Mix 2	2.6	2.72	1.21	1356	SIKA 512	Naphthalene	CMTL
3	Mix 3	2.49	2.69	1.06	1351	Fast SP 875	Naphthalene Sulphonate	BSL
4	Mix 4	2.6	2.65	1.9	1340	Fast SP 875	Naphthalene Sulphonate	ZKB1
5	Mix 5	2.6	2.65	1.9	1340	Sikamint HRM	Naphthalene	ZKB2
6	Mix 6	2.65	2.67	1.3	1390	Fugen 4400	Naphthalene	HCS
7	Mix 7	2.49	2.694	1.06	1351	Fast SP 875	Naphthalene Sulphonate	UBA
8	Mix 8	2.45	2.73	1.38	1365	BASF 850	Naphthalene	ICS

FM¹ = fineness modulus; Gs² = specific gravity; Abs.³ = water absorption (%); L.D⁴ = loose density (kg/m³).**Table 2**

Physical properties of coarse aggregate (Sargodha crush).

Sr. No	Design Sources	Coarse aggregate				
		Gs	Abs.	L.D ¹	L.D ²	L.D ³
1	UET	2.65	1.0	1394	1394	1394
2	CMTL	2.78	0.41	1356	1372	1387
3	BSL	2.68	0.77	1351	1429	---
4	ZKB1	2.84	0.41	1340	1346	1362
5	ZKB2	2.84	0.41	1340	1346	1362
6	HCS	2.82	0.39	1390	1390	1390
7	UBA	2.68	0.77	1351	1429	----
8	ICS	2.67	0.85	1365	1365	-----

Gs = Specific gravity; Abs. = water absorption (%), L.D = loose density (kg/m³); 1 = 16–25 mm; 2 = 10–16 mm; 3 = 5–10 mm.**Table 3**

Mix proportion of eight types of concrete mix designs.

Mixture Type	Cement	Crush	Sand	Admixture	Water	w/c
UET	450	1130	661.5	4.95	184.5	0.41
CMTL	415	1035	824	6.60	170	0.41
BSL	450	1046	699	4.95	200	0.41
ZKB1	400	1147.6	783.6	5.66	163.6	0.36
ZKB2	425	1115.6	761.7	4.01	176.3	0.37
HCS	425	1122	720	5.60	170	0.40
UBA	450	1046	699	4.95	200	0.41
ICS	430	1059	720	4.30	200	0.42

considering stakeholder and industry requirements to reach an unbiased decision.

Material quality, cost, performance and durability are considered as the most common selection criteria to achieve a comprehensive concrete mix design. On the other hand, material source location, supplier company profile and their payment method may also be considered. With initiatives towards resource conservation, aspects such as a reduction in carbon footprint, energy efficient construction and least energy intensive material sourcing and production may also be considered. Based on the most commonly used stakeholders' requirements, eight criteria were identified for selection of optimal mix design. These were; conservation of raw materials, water conservation, environmental impact, economy, w/c ratio, 7 and 28 days compressive strength and density of the designed concrete mix.

Clinker; an essential component of cement creates a high amount of CO₂ emission and employs energy intensive processes for its sourcing and production, as discussed in Section 1. Use of dynamite and other heavy equipment and machinery for quarrying limestone also disrupts the natural environment and creates a nuisance for neighboring localities. Moreover, the issue of natural resource depletion (coarse and fine aggregate) to maintain the balance in the ecosystem and natural environment has also been debated. Therefore, the preservation of raw materials i.e. cement, sand, and coarse aggregate was selected as an essential criterion.

Concrete construction encompasses the cost of sourcing of ingredients like limestone, fine aggregate and coarse aggregate along with the cost of transportation to the site. As the cost of reinforced concrete work forms an integral part of the project cost, therefore, the economy was also identified as an important criterion for selection of optimum concrete mix design. Market rate system (MRS) Punjab rates for Lahore [37] have been used for quantifying the cost of each mixture. The environmental impact of the different design mixes will also differ, as the amount of cement varies with the designed proportions. Thus, the corresponding environmental influence was also selected as a significant criterion. The Intergovernmental Panel on Climate Change (IPCC) standard CO₂ emissions factor for clinker production for Pakistan has been used. The assumed fraction of lime (CaO) used in clinker production is approximately 64.6% [38], which is almost the same as mentioned in the article [34]. Resource conservation includes the optimal utilization of all resources including water. The minimum amount of water to achieve required workability, performance and durability was another major criterion for selection. Another significant criterion was 7 and 28 days compressive strength. As per ACI Standard [21,39], 70% and 100% design strength is desired at 7 and 28 days respectively. The analysis is carried out by prioritizing the minimum values of actual concrete strength, to the required design strength. The selected compressive strength of concrete mix design at 7 and 28 days, was 19 MPa and 28 MPa with corresponding

design strength of 36 MPa. Studies show that high early strengths (at 7 days) are achieved by using excess quantity of cement, which is against the sustainable consumption of natural resources [22]. This mix design was aimed to be economical as well as durable by consumption of minimum cement content. The density of concrete was another important parameter linked to its durability. Well-graded aggregate with minimum porosity and maximum density/unit weight to avoid chloride penetration was preferred [40]. Selected criteria are listed in Table 4.

Physical and chemical properties of the aggregates; specific gravity, water absorption, fineness modulus, petrographic analysis, admixture constituents have not been given priority in selection of criterion to achieve a suitable mix design. These factors were overlooked due to geographical applicability of the case study on which the work is applied. Locally available aggregates are used in mix design, which are collected from similar sources therefore, have similar physical and chemical properties. Such a practice is common in case of all major construction projects in Pakistan. Also, these criteria fulfill the minimum requirements of the stakeholders and industry and hence remain similar throughout the projects. In this study, Sargodha crush and Lawrence pur sand (locally sourced) with identical properties were used in all mix designs. Therefore, such properties were not selected as criteria nor given due importance for selection process.

3. Analytical techniques

This study aimed at selection of an eco-friendly and sustainable concrete mix design based on eight criteria enlisted in Table 4. The MCDM techniques adopted for the optimal selection of concrete mix design were; Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Elimination et Choice Translating Reality (ELECTRE) and Analytical Hierarchy Process (AHP). The analysis process by these techniques is explained in the following sub-sections.

3.1. Technique for order preference by Similarity to ideal solution (TOPSIS)

TOPSIS uses a practical and beneficial approach to select the best alternative among all the available alternatives by its closeness to positive ideal alternative and farthest from negative ideal alternative [41]. Basically, the technique compares the set of

alternatives by identification of weights for each criterion, normalizes their score and calculates the distance between each alternative and the ideal alternative. This approach helps in providing a realistic analysis as compared to non-compensatory methods whose results are based on hard cutoffs. The detailed procedure for the application of TOPSIS is explained in the author's previous works [42–45]. Incorporation of experimental values in TOPSIS is explained in Fig. 1, eight alternatives (mix designs) and eight criteria (Table 4) were used to establish decision matrix and then it was normalized by using expression mentioned in Fig. 1. The best alternative was selected as having a minimum value of all criteria except density/unit weight, which has the maximum value. Separation matrix was established by separating the best and worst alternatives and finally, relative closeness coefficient was evaluated, and the highest value of this coefficient presents the optimal concrete mix design. The schematic methodology of TOPSIS is illustrated in Fig. 1.

3.2. Elimination et Choice Translating Reality (ELECTRE)

ELECTRE is also known as the “outranked method” for decision making that helps to choose the best option among different options by choosing, ranking and sorting it [28]. This technique has two steps. Outranking relations among the set of criteria are developed to compare each alternative in a comprehensive manner. The second step comprises of utilizing recommendations obtained from the first step and then ranking and sorting them. This method usually discards unacceptable alternatives to ease the decision-making process. Up to step of normalization of decision matrix the procedure of ELECTRE is same as TOPSIS. In the next step, concordance set, and matrix are formed along with the discordance set and matrix, then dominance matrix is formed. Finally, the elimination of the worst alternative is done by which an optimized selection/decision is obtained. The detailed procedure for the application of ELECTRE is illustrated in Fig. 2.

3.3. Analytical hierarchy process (AHP)

AHP is a structured and organized technique to analyze complex decisions. It connects the decision makers to the best option by linking their goal and understanding of the problem. The technique uses a systematic hierarchy comprising of goal at the top, criteria as a middle layer and all the possible alternatives as the last layer of hierarchy. The complex problem is disintegrated into sub-elements by making an appropriate hierarchy and then making a comparative analysis among them [46]. Decision makers can then compare the alternatives with respect to their impact on the element above them in a hierarchy. In this work, the goal is to optimize a concrete mix following the mentioned criteria (Table 4) and the eight alternative mix designs (Tables 1–3). Guidelines for the application of AHP on the multifaceted problem are illustrated in Fig. 3.

As discussed, the first step is to identify the goal for the complex problem which is; to evaluate and select the best concrete mix design based on selected criteria. The second step is to decompose the complex problem in a hierarchy in which the first level represents the goal. In this work, the goal is to select such a mix design which exhibits sustainability in terms of conservation of natural materials and environmental impact. The second level represents the eight criteria selected for analysis; consumption of raw materials, cost of materials, environmental impact, amount of water, w/c ratio, compressive strength at 7 days and 28 days and the unit weight of concrete. The last level represents eight alternatives (eight mix designs).

Table 4
List of criteria with reasoning.

Sr. No	Criteria	Reason
1	Raw Materials	Resource conservation (minimum amount of cement, coarse and fine aggregate).
2	Cost of Materials/Economy	Most economical mix design achieved by the minimum use of the concrete constituents.
3	Environmental Impact	To ensure eco-friendly mix design using minimum use of the cement.
4	Amount of Water	To select a resource conservative mix design i.e. the minimum amount of water ensuring required workability and durability of concrete.
5	W/C Ratio	Minimum amount of water to cement (w/c) ratio was prioritized in this regard to producing a durable concrete mix.
6	Compressive Strength (7 days)	19 MPa cylindrical compressive strength at 7 days
7	Compressive Strength (28 days)	28 MPa cylindrical compressive strength at 28 days
8	Density/ Unit Weight	To ensure a durable mix design having maximum density/unit weight, well-graded aggregate with minimum voids

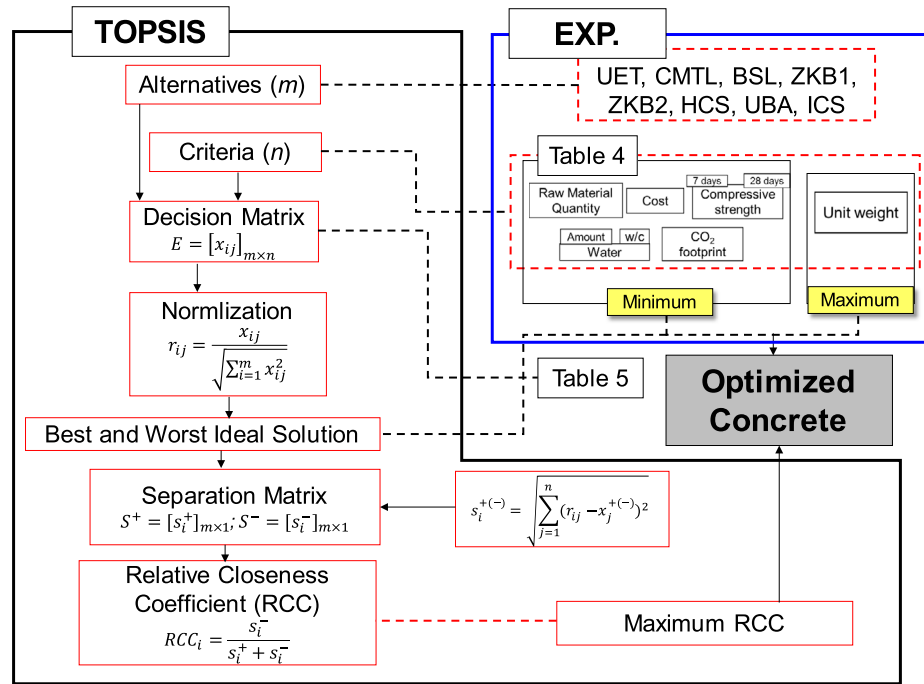


Fig. 1. Schematic diagram of analysis by TOPSIS.

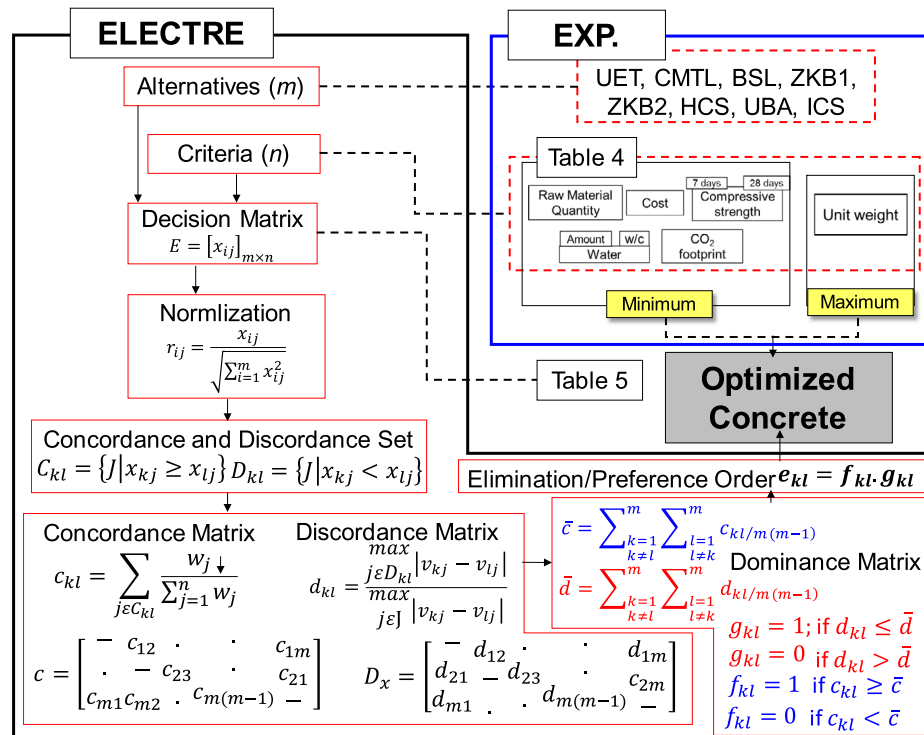


Fig. 2. Schematic diagram of analysis by ELECTRE.

The third step is the assessment of the importance of one criterion over another for which a pairwise comparison is made through a decision matrix. Priority weights for each criterion are determined through the Eigenvector, followed by a priority vector. The inconsistency of pairwise comparison is then determined

through consistency index (CI), consistency ratio (CR) and random index (RI). If the value of CI and RI exceeds the maximum acceptable limit (0.1), this will indicate the inconsistency of pairwise comparison and must be discarded. The last step is the evaluation of the overall priority vector which takes into account the priority

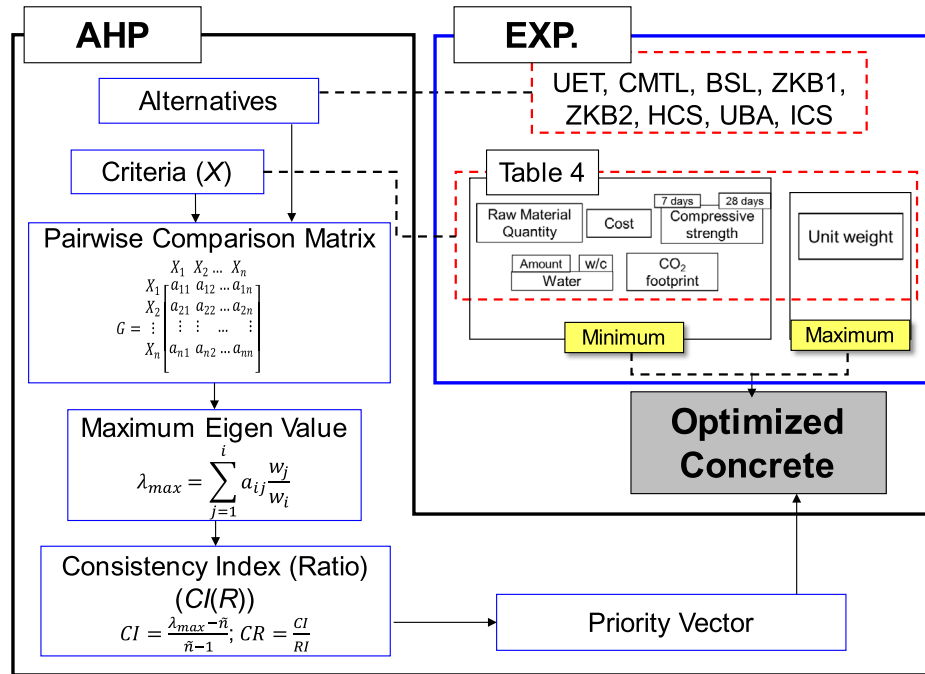


Fig. 3. Schematic diagram of analysis by AHP.

vector of criteria and the priorities of all alternatives. The result thus obtained is in terms of global weights and the alternatives are prioritized accordingly.

4. Results and discussion

4.1. Raw Materials/Unit weight

The total amount of raw materials; cement, sand, coarse aggregate, admixture and water used for each mix design was calculated from Table 3. The amount of raw materials, varied from 2195 to 2331 kg/m³, is presented in Fig. 4(a). The maximum raw materials were used in ZKB1 mixture and minimum raw material was utilized in BSL and UBA mixtures. An average amount of cement (by weight) in all concrete mixes was 19.14%, whereas, the average amount of sand and coarse aggregate was 35.56% and 48.29%, respectively. Volumes of raw materials were also calculated by multiplying their weights with corresponding densities (Fig. 4(b)). Average volume of each constituent; cement sand and

coarse aggregate were 19.29%, 30.77%, and 49.94%, respectively. The overall unit weight of these concrete mixes varied from 2400 to 2500 kg/m³ (Table 3). The concrete durability is accessed indirectly by inferring that the mix having maximum unit weight with densified structure is the best. But such a mix would require more raw materials and its cost will increase. Therefore, an optimized mix design considering both cost and material conservation without neglecting its durability must be selected.

4.2. Cost

Cost of each mixture was calculated by using the corresponding quantities mentioned in Fig. 4(b). MRS Punjab, Pakistan rates (2nd Bi-Annual-2018) were used as the reference for calculation of the cost of each constituent, which also included the transportation cost of raw materials [37]. The cost of one bag of cement was 538 Pakistani rupees (PKR), cost of sand, coarse aggregate and admixture were PKR. 37 per cft (cubic ft). PKR 40 per cft and Rs. 100 per liter, respectively. The calculated cost of each mix is

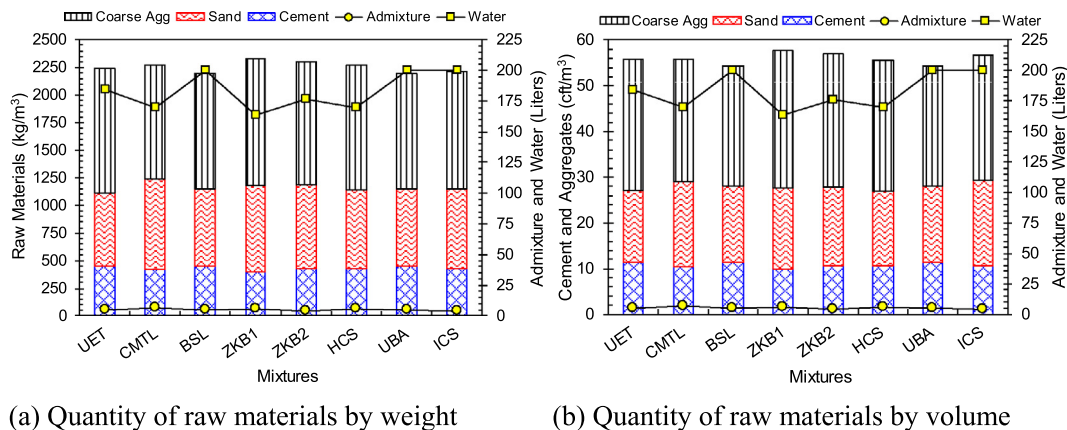


Fig. 4. Amount of raw materials; cement, sand, coarse aggregate, admixture and water, in all types of mixes.

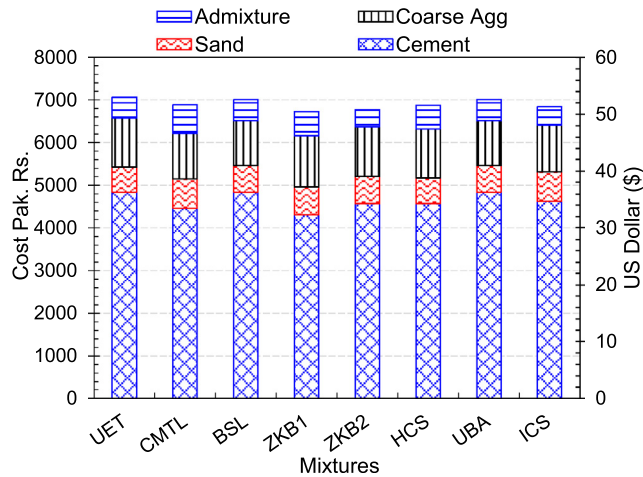


Fig. 5. Cost per cubic meter for all types of mix designs.

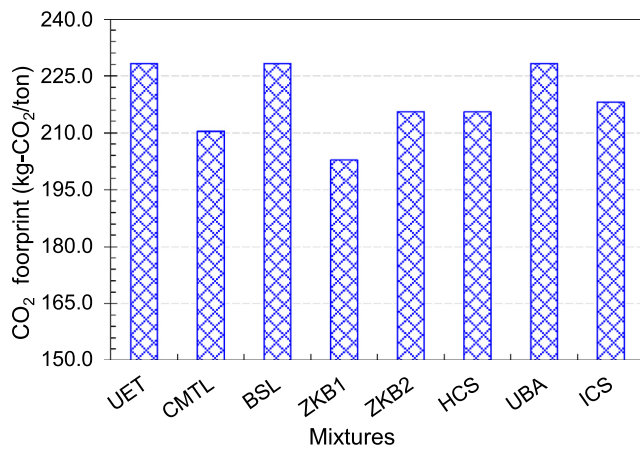


Fig. 6. CO₂ emission for all types of mixtures.

mentioned in Fig. 5 and Fig. 6. The average contribution of cost by cement and sand was 67.14% and 9.23% respectively among the eight mix designs. It is evident that the amount of cement in mix design directly raises its cost as it is the one material with highest cost among concrete constituents. Although coarse aggregate occupied the maximum amount of volume in each concrete mix, its contribution to cost is only 16.20%. The admixture owing to its small amount in the mixes contributed to an average cost of 7.43%. The maximum cost was found to be PKR 7,069 per cubic meter for UET mix and the minimum cost was PKR 6,727.7 per cubic meter for ZKB1 mix.

4.3. Carbon dioxide footprint

A large amount of carbon dioxide (CO₂) is generated in the manufacturing of concrete, especially during the production of cement. This is because of the fact that during calcination of raw materials, CO₂ is emitted due to the utilization of fuel by equipment/machinery, electricity and for transportation [10]. The approximate amount of CO₂ (kg-CO₂) emitted per ton by the constituents of concrete was provided by codes and several studies [47,48]. The life cycle of concrete must be considered for the precise assessment of CO₂ footprint. It is evident that cement has the greatest CO₂ footprint of 80% in comparison to the other raw materials used in concrete [49]. The molecular weight ratio of CO₂/CaO is 0.785. When multiplied, these figures give the final emission factor for clinker,

0.5071 tons of CO₂ per ton of clinker (507.10 Kg-CO₂/ton). Here, in this work, 507.1 kg-CO₂/ton of cement was used to determine the corresponding CO₂ footprints. Fig. 6 illustrates the CO₂ footprint of eight types of mix designs used in this study. The amount of CO₂ footprint varies from 203 to 228 kg of CO₂ footprint per ton of concrete. The maximum value for UET mixture and the minimum value for ZKB1 mixture was observed. The average amount of CO₂ was 218.4 kg-CO₂/ton. Although CO₂ footprint has a significant adverse impact on the environment still it is often ignored by the stakeholders while selecting a concrete mix design. To ensure environmental sustainability, the selection of an appropriate mix design by assessment of CO₂ footprint should be done.

4.4. Compressive strength

Compressive strength test was performed on all mix designs after 7 days and 28 days of casting, according to ASTM guidelines [50]. Average compressive strength of three specimens was calculated, for both 7 and 28 days (Fig. 7). It was observed that measured compressive strength exceeded the target compressive strength at 7 and 28 days for all mix designs. An increase in compressive strength from target strength was observed for both ages (43–120% at 7 days and 28–58% in compressive strength at 28 days). The amount of increment for each mix is presented in Fig. 7. For sustainable production of concrete, it is recommended to use mix design which has compressive strength close to the target strength. This will ensure conservation of raw materials and a corresponding decrease in its environmental impact. The factor of safety is already incorporated during the design phase of any concrete structure, by increasing the design strength to a tune of 30% as compared to the actual strength. Any additional amount may enhance structural performance, but it can impose a threat to sustainable construction. Therefore, the mix design qualifying the criteria of closest compressive strength to target design compressive strength should be selected. In this case, ZKB1 mixture's compressive strength was found to be closest to the target compressive strength at 7 and 28 days.

The calculated amounts of raw material, cost per cubic meter, amount of water used, w/c ratio, the compressive strength at 7 and 28 days and unit weight of the concrete of each design mix is listed in Table 5.

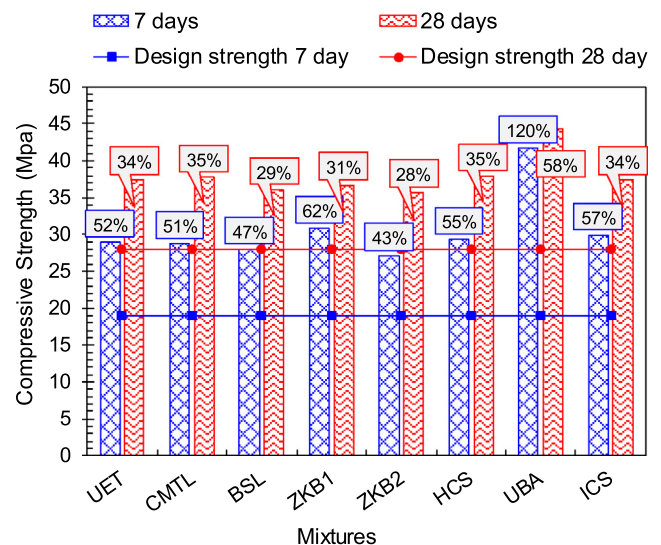


Fig. 7. The compressive strength of all types of mix designs.

Table 5

The calculated amount of eight selected criteria corresponding to each mix design.

Sr. No.	Mix design	Raw material	Cost/m ³	CO ₂ footprint	Water	w/c ratio	Compressive strength (MPa)		Unit weight
		kg/m ³	Pak. Rs.	kg- CO ₂ /ton	Liter		7 days	28 days	kg/m ³
1	UET	2242	7069	228.2	184.5	0.41	28.9	37.4	2431.0
2	CMTL	2274	6882	210.4	170.0	0.41	28.7	37.7	2450.6
3	BSL	2195	7009	228.2	200.0	0.41	27.9	35.9	2400.0
4	ZKB1	2331	6728	202.8	163.6	0.36	30.8	36.7	2500.5
5	ZKB2	2302	6780	215.5	176.3	0.37	27.2	35.7	2482.6
6	HCS	2267	6877	215.5	170.0	0.40	29.4	37.8	2442.6
7	UBA	2195	7009	228.2	200.0	0.41	41.7	44.2	2400.0
8	ICS	2209	6837	218.1	200.0	0.42	29.9	37.4	2413.3

5. Prioritization of concrete mix design

A decision hierarchy was formulated with goal, criteria and alternatives. All the criteria were assigned weights and evaluated with MCDM techniques; TOPSIS, ELECTRE, and AHP. Results of each technique were compared for equal preference and with high preference/importance assigned to different criteria. It is obvious that contractors, keeping in view the profitability factor, prefer a mix design with minimum cement content, however the consultants/clients, keeping in view an extra factor of safety, prefer and selected the concrete mix design, having maximum cement content with higher unit weight with well graded aggregates etc. at their projects. So, different weight factors were also used for setting the importance/preferences for each criterion, which were assumed after discussions with the relevant professional workers in the construction industry at managerial level or above. The list of criteria along with the importance and weight factor is mentioned in Table 6. Results of all techniques were compared with each other for equal preference and with high preference assigned to different criteria and are explained in the following sub-sections.

5.1. Selection by TOPSIS

The best ideal alternative was selected by TOPSIS by using equal importance to each criterion as mentioned in Table 6. The weight factor for each criterion was 0.125 and the sum of all weight factor was 1.000. List of preferences was estimated according to the value of RCC (Relative Closeness Coefficient), highest the RCC high will be the preference and vice versa. By assigning equal preference the best and worst alternatives were ZKB2 and UBA, respectively. While ZKB1 was at second preference which was shifted to the fourth position when the analysis was conducted by giving higher

importance to the raw material criterion (Table 6). However, ZKB2 and UBA were again the best and worst alternatives, respectively. By setting the importance to the cost criterion, the preference of each mixture was like the selection of equal preference. For environmental consideration, the importance of CO₂ footprint was also incorporated. The first preference came out as ZKB1 instead of ZKB2, whereas ZKB2 was shifted to second preference, the last preference (UBA) was still same. Water is the natural resource and its conservation is of high importance all over the world. The importance to this criterion was also given (Table 6) and the best ideal solution was ZKB2 while the worst solution was UBA and same alternatives were prioritized while giving the preference to the compressive strength value of the concrete. Fig. 8 presents the comprehensive summary of preferences of each alternative by giving equal importance and high importance to selected criteria.

5.2. Selection by ELECTRE

In ELECTRE, the worst alternative was eliminated by following the procedure illustrated in Fig. 2, the value of the criterion with a maximum number of 1 than 0 was eliminated from the elimination matrix. The number of zeros counted and a maximum number of zero indicates the best ideal alternative, whereas the maximum number of ones indicates the worst solution. Fig. 9 represents the number of zeros of each mixture by giving the importance to the criteria. It was observed that ZKB1 or ZKB2 was the best option in all scenarios of assigned preferences and having a maximum number of zeros (8) among eight alternatives (mix design). The second-best alternative with maximum 7 number of zeros was BSL when importance was given to raw material criterion. Whereas CMTL was the second-best option under the importance of compressive strength criterion. The last option for mix design was

Table 6

Criteria with preferences and corresponding weight factors.

Criterion	Raw material	Cost/m ³	CO ₂ footprint	Water	w/c ratio	Compressive strength (MPa)		Unit weight
						7 days	28 days	
Imp.*	Equal	Equal	Equal	Equal	Equal	Equal	Equal	Equal
W.F.**	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
Imp.	High	Equal	Equal	Equal	Equal	Equal	Equal	Equal
W.F	0.300	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Imp.	Equal	High	Equal	Equal	Equal	Equal	Equal	Equal
W.F	0.100	0.300	0.100	0.100	0.100	0.100	0.100	0.100
Imp.	Equal	Equal	High	Equal	Equal	Equal	Equal	Equal
W.F	0.100	0.100	0.300	0.100	0.100	0.100	0.100	0.100
Imp.	Equal	Equal	Equal	High	High	Equal	Equal	Equal
W.F	0.100	0.100	0.100	0.200	0.200	0.100	0.100	0.100
Imp.	Equal	Equal	Equal	Equal	Equal	High	High	Equal
W.F	0.100	0.100	0.100	0.100	0.100	0.200	0.200	0.100

Imp.* = importance; W.F.** = weight factor.

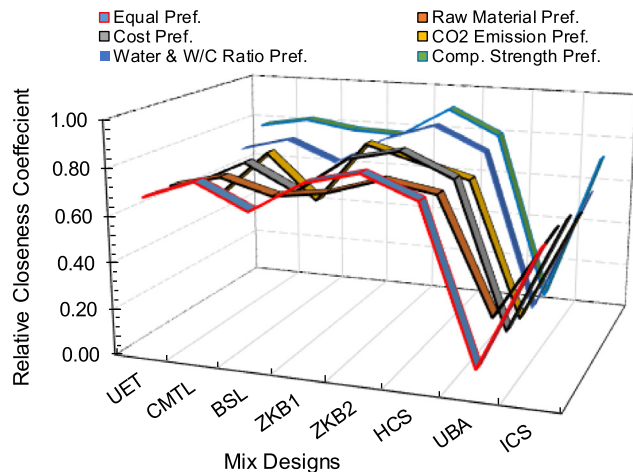


Fig. 8. Summary of selection of mix designs by TOPSIS by setting designed importance to criteria.

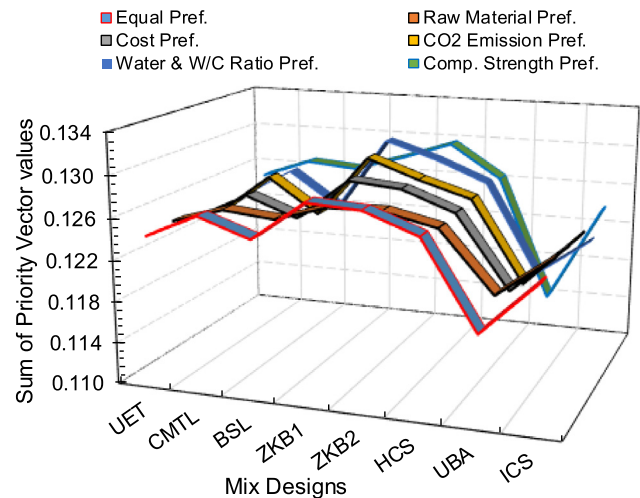


Fig. 10. Summary of selection of mix design by AHP by setting designed importance to criteria.

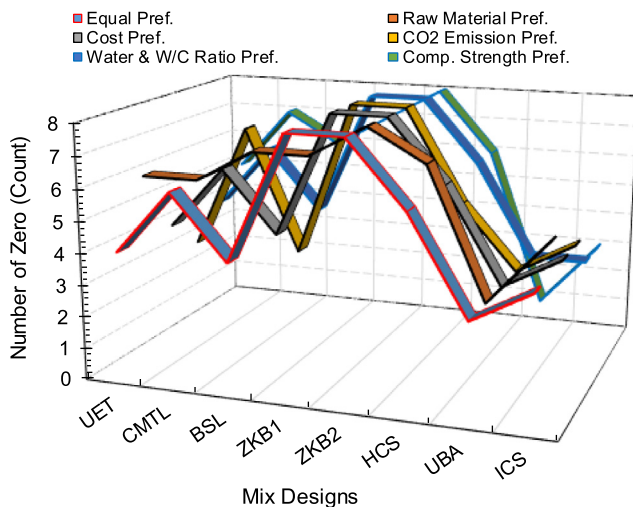


Fig. 9. Summary of selection of mix design by ELECTRE by setting designed importance to criteria.

UBA, the number of zeros was 3 in all scenarios except under the importance of compressive strength where it was only 1. ICS alternative was the second last option for the alternatives in all scenarios except the case where water conservation had higher importance than other criteria, then BSL was found to be as the second option.

5.3. Selection by AHP

Third MCDM technique, AHP was also applied to verify the selection of optimized concrete mix designs. In AHP, pairwise comparisons were made among eight alternatives (mix designs) by assuming the equal importance as well as giving higher importance to criteria as mentioned in Table 6. Priority matrix and its normalization by using maximum Eigen value against each criterion were done in the next step as illustrated in Fig. 3. Consistency ratio of 0.1 was maintained and the priority vector was calculated and the sum of all priority vectors against each criterion described the order of priority for the selection of optimized concrete mix. The concrete mix design with the highest sum of the priority vector is selected. The sum of priority vector for each alternative with different importance is presented in Fig. 10. It was observed

that UBA is the worst alternative in all scenarios and first preference is ZKB1 for equal importance, cost importance, CO₂ footprints importance, and water importance, whereas ZKB2 was the first preference for raw material and compressive strength importance.

5.4. Comparison of preferences among MCDM techniques

A comparison of preferences was made among the three MCDM techniques. Fig. 11 presents the comparison for each technique with respect to the assigned priority of each criterion. In all cases, the worst option of mix design is UBA design mix, whereas some difference is available in first preference. In case of equal importance of each criterion, the best option was ZKB2 by TOPSIS and ELECTRE, whereas ZKB1 was the best option by AHP followed by ZKB2 as second option as depicted in Fig. 11(a). In the case of raw material priority, the optimized concrete design mix was ZKB2 by all MCDM techniques (Fig. 11(b)). Similarly, alternative ZKB2 was selected as the best option, while prioritizing the compressive strength criteria (Fig. 11(f)). ZKB1 was selected as the optimized mix design under the priority of CO₂ footprint (Fig. 11(d)). For the priority of cost and amount of water criteria, the best option selected by TOPSIS and ELECTRE was ZKB2, whereas ZKB1 was selected by AHP (Fig. 11(c) and Fig. 11(e)). Table 7 presents the best and worst alternatives for each MCDM technique and close correspondence was observed among various preferred alternatives.

5.5. Application to real structures

The work done in this study is applied to a case study project titled 'Pakistan Kidney & Liver Institute Hospital, Lahore, Package-C1 (PKLI project)'. The reason behind selection of that particular project is that one of the authors is working on this project and has sufficient knowledge of the requirements of the project and stakeholders. The data which is used in quantification and selection of the criteria for decision making, is taken from the case study project through discussions and interviews of the stakeholders from the same project. The optimized concrete mix design was selected, by three MCDM techniques, and compared with the design mix (UET), already being used at the project (PKLI project). It is a usual practice that the consultant selects the mix design having the maximum amount of cement content and having maximum compressive strength. So, despite the availability of all the eight mix designs (alternatives), UET mix design was selected by

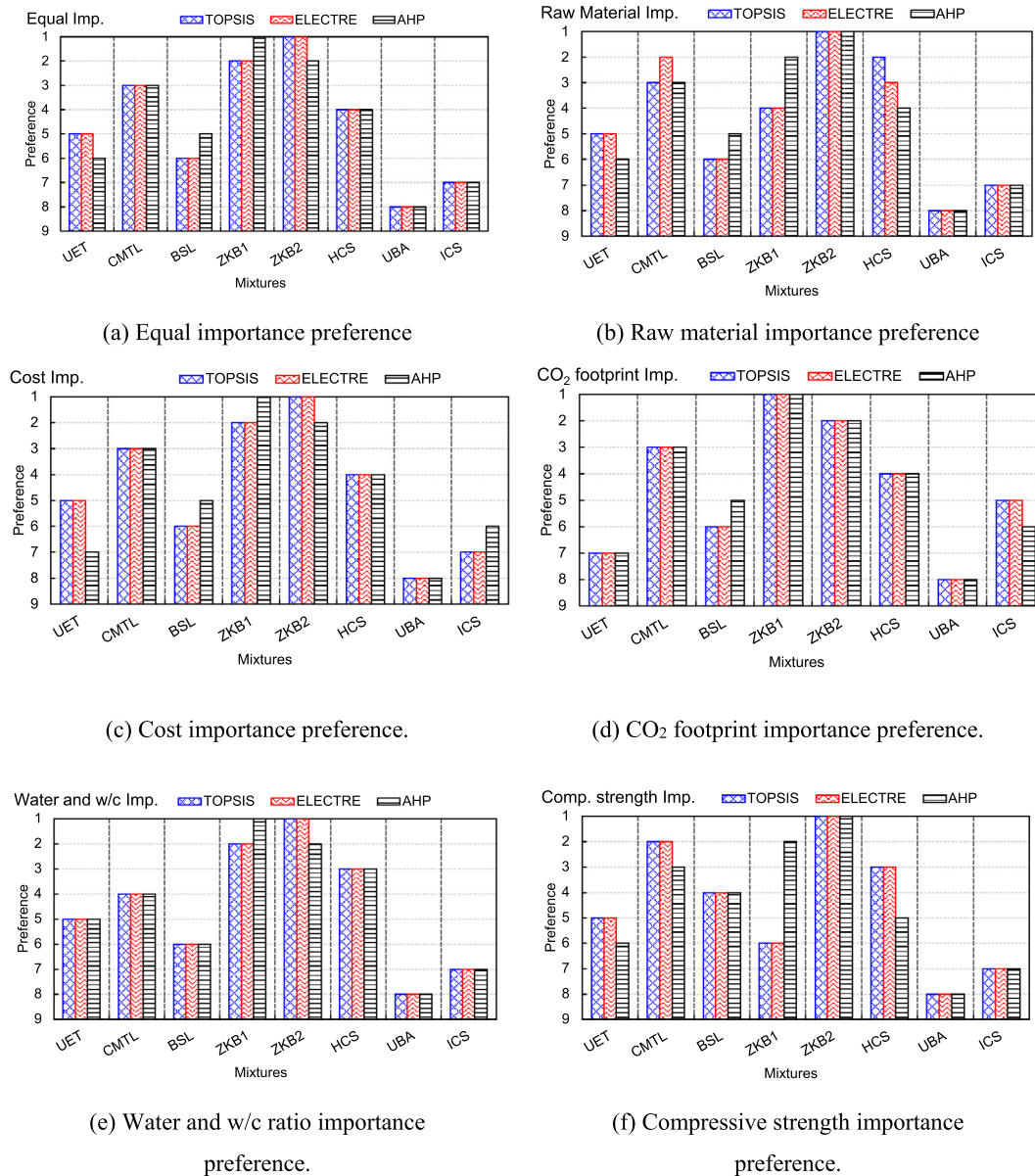


Fig. 11. Comparison of ranking of concrete mix between MCDM techniques with different importance preferences.

Table 7

Best and worst alternatives among all concrete mixes by MCDM techniques.

Priority	Best Alternative			Worst Alternative		
	TOPSIS	ELECTRE	AHP	TOPSIS	ELECTRE	AHP
Equal Pref.	ZKB2	ZKB2	ZKB1	UBA	UBA	UBA
Raw Material Pref.	ZKB2	ZKB2	ZKB2	UBA	UBA	UBA
Cost Pref.	ZKB2	ZKB2	ZKB1	UBA	UBA	UBA
CO ₂ footprint Pref.	ZKB1	ZKB1	ZKB1	UBA	UBA	UBA
Water & W/C Pref.	ZKB2	ZKB2	ZKB1	UBA	UBA	UBA
Comp. Strength Pref.	ZKB2	ZKB2	ZKB2	UBA	UBA	UBA

the consultant of PKLI project, keeping in view the safety and durability factors at the time of mix design selection. All results by MCDM techniques revealed that the selection was not optimized as resources (raw materials including water) can be saved and profit can be increased, without compromising the strength and durability requirements. Quantitatively, benefits by using the analytical selection were estimated by using BOQ (bill of quantity) to

be executed at PKLI-C1 project, where 23567 m³ concrete of 28 MPa was required. The price of one cement bag was 538 PKR, and the rate of fine aggregate and coarse aggregate was PKR 37 and PKR 40 per cubic feet respectively, (according to MRS Punjab Rates for Lahore) [37]. It is concluded that the contractor could get a remarkable profit of around 4.5 million Pak. Rs. (37500/- US Dollar), which is almost 11% of the bid cost of concrete, if ZKB2

Table 8

Comparison of UET and ZKB-2 mix design in terms of profit, resource conservation and environmental performance.

Design Source	Mix Proportions by Volume	Resource Conservation				Environmental Impact (CO ₂ Footprint from Cement)
		Cement (kg)	Sand (cft)	Aggregate (cft)	Water (L)	
UET	1 : 1.47 : 2.51	450	15.85	28.63	184.5	228.2
ZKB-2	1 : 1.65 : 2.81	425	17.15	29.29	176.3	176.3
Difference		25	-1.3	-0.66	8.2	51.9
Rate		538	37	40		
Amount		269	-48.5	-26.4		
Saving (Rs.)		194.5				
Net Saving as analysis		4,583,780. Pak. Rs.			193,249 (L)	1223127 kg.

mix design would have been implemented, at PKLI project, rather than UET mix design. In addition, about 193,000 L of water, a natural resource, could have been saved. The CO₂ emissions could also be reduced considerably, the comprehensive summary of all the parameters is also described in Table 8.

6. Conclusions and recommendations

This working has resulted in prioritizing the available alternatives of eight concrete mix designs considering conservation of materials and environmental impact. The amount of raw material, their cost, CO₂ emission and finally 7 and 28 days compressive strength were considered for evaluation. All mix designs fulfil the requirements of mechanical and durability performance as evident by the concrete compressive strength in the current work. But, ZKB1 has the least cost and CO₂ emission and may be a more appropriate choice for keeping a balance among durability, economy, resource conservation and ecofriendly processes (criteria).

Based on the different weights assigned (preference) to the criterion, the analytical techniques provided the best and worst alternative. A resource efficient concrete mix design is selected by assigning priority to the criterion of raw material, amount of water and water to cement ratio, which are significant for resource conservation. ZKB1 and ZKB2 were identified as the most suitable alternative and UBA mix design as the worst alternative. The results from the three MCDM techniques are correlated with respect to the assigned preference which confirms their effectiveness for good decision making. It was also concluded from one case study, where UET mix design was used instead of ZKB-1, that about 4.5 Million PKR (Pakistani Rupees.), about 190,000 L water can be saved, and CO₂ emissions can also be reduced by an amount of 1223127 kg.

The research can easily be applied by varying criteria and alternatives and by assigning different weights. The working incorporates the preferences of various stakeholders which can influence the selection of the prioritized mix design. Hence, these methods are flexible and can be altered according to the importance of parameters and corresponding alternatives. These methods can be effectively applied on a selection of the most suitable alternatives in the concrete construction industry over a wide range of field scenarios and to the satisfaction of the stakeholders.

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.

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