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Selecting optimized mix proportion of bagasse ash blended high performance concrete using analytical hierarchy process (AHP)

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Abstract. Apart from strength properties, durability, toughness and workability are also important criteria in defining the performance of a concrete structure. Hence “High Performance Concrete (HPC)” is introduced. It is different from high strength concrete and can have various applications. In this paper, the properties (Mechanical and Durability) of High Performance Concrete blended with bagasse ash at 5%, 10%, 15% and 20% are studied. However, it is difficult to analyze the performance based on different properties obtained from different experiments. Hence it is necessary to combine all the criteria/properties into a single value to obtain a result by a technique called Analytical Hierarchy Process (AHP).It is an effective tool for dealing with complex decision making, and may aid the decision maker to set priorities and make the best decision. In addition, the AHP incorporates a useful technique for checking the consistency of the decision maker’s evaluations, thus reducing the bias in the decision making process.

Keywords: bagasse ash; high performance concrete; analytical hierarchy process (AHP); mechanical properties; durability properties

1. Introduction

The most versatile and durable material in the field of construction is concrete. But it is subjected to continuous deterioration without any precautionary measures during the production and design period. A concrete mixture, which possesses high strength and durability compared to conventional concrete, is known as “High Performance Concrete (HPC)”. It comprises of the same materials as the conventional concrete, but the use of SCMs enhances the durability, workability and strength qualities to a great extent. Many kinds of supplementary cementitious materials (SCMs) such as silica fume, ground granulated blast furnace slag and fly ash are used along with a super plasticizer to form HPC. The initial cost of HPC is higher than conventional concrete. But since it has a prolonged service life, the repair and maintenance costs of the structure during its service period are reduced, and hence the overall costs are minimized. Various mechanical and durability properties are experimentally studied for HPC. However, it is difficult to assess their performance based on the results of these properties.

For evaluating, assessing and ranking various alternatives in different fields and industries Multi-Criteria Decision Making (MCDM)is used. The criteria are also known as “objectives” or “attributes”. Hence, this method is also known as Multi-Objective Decision Making (MODM) or Multi-Attribute Decision Making (MADM). Various MCDM techniques are Weighted Sum Method (WSM), Weighted Product Method (WPM), Technique for order preference by similarity to ideal solution (TOPSIS) and Analytic Hierarchy Process (AHP).

Research problems involving selection of optimal parameters from a set of varying alternatives adapts MCDM to achieve the best solution. Alternatives, criteria, relative importance of each criteria and performance of criteria are the four parts that make up the decision table in any MCDM method. Performance measurement models for manufacturing organizations, robots performance in industries, selection of best mobile phone, evaluation of projects, design of products, selection of work materials, etc., are a few applications of MCDM techniques.

Analytical Hierarchy Process (AHP) is the most widely used technique in the decision making process. It was originally developed by Prof. Thomas L. Saaty in 1980. The AHP considers a set of evaluation criteria, and a set of alternative options among which the best decision is to be made. It is important to note that, since some of the criteria could be contrasting, it is not true in general that the best option is the one which optimizes each single criterion, rather than the one which achieves the most suitable trade-off among the different criteria.

The AHP generates a weight for each evaluation criterion according to the decision maker’s pair-wise comparisons of the criteria. The higher the weight, the more important is the corresponding criterion. Next, for a fixed criterion, the AHP assigns a score to each option according to the decision maker’s pair-wise comparisons of the options based on that criterion. The higher the score, the betteris the performance of the option with respect to the considered criterion. Finally, the AHP combines the criteria

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Table 1 Different applications based on AHP

S.No.	Authors	Application
1	Balali *et al*. (2014)	Selecting the best building structural system for thermal insulation out of five alternatives based on criteria like cost, ease of construction, energy saving, dead load, number of stories and life cycle time using AHP and PROMETHEE methods
2	Kamaakchaoui *et al*. (2016)	Helping customers in selecting best complementary products from four alternatives under various criteria like product's feature, satisfaction, need and interest to classification using AHP.
3	Chakladar and Chakraborty (2008)	Selection of best non-traditional machining process fromnine alternatives under various performance criteria using AHP.
4	Erdebilli and TErkan (2012)	Selection of best supplier from three suppliers for a company in Iran using AHP.
5	Ince *et al*. (2017)	Selection of the best Learning Object Repositories (LOR) used in storing learning objects (LOs) and metadata using combined TOPSIS and AHP. The LORs are the alternatives and the various LOs and metadata are the criteria used.
6	Ishizaka and Labib (2009)	Selection of best automobile from five alternatives under criteria like initial cost, maintenance, prestige and quality using software package 'Expert Choice' which uses AHP.
7	Jin (2014)	Discussion of therisk evaluation of construction stage for building engineering projects based on Analytical Hierarchy Process (AHP), which would be beneficial to perfect the practice of the risk evaluation of construction stage for building engineering projects.
8	Socaciu *et al*. (2016)	Selection of best Phase Change Materials (PCMs) for vehicles for thermal comfort using AHP.Ten alternatives are selected and are analysed using AHP based on seven criteria
9	Lin *et al*. (2008)	An adaptive AHP approach that uses a soft computing scheme, Genetic Algorithms, to recover the real number weightings of the various criteria in AHP and provides a function for automatically improving the consistency ratio of pair-wise comparisons is studied
10	Lin *et al*. (2015)	Investigation of the current practices of the available procurement methods for building maintenance work in public universities and identify the procurement selection criteria to develop an effective decision-making framework using AHP.
11	Mansor *et al*. (2013)	Studying the advantages of using hybrid natural and glass fibres reinforced polymer composites over synthetic fibres to be used in automotive brake lever. Eleven natural fibres are studied and their performance is evaluated based on various criteria using AHP.
12	Hudymacova *et al*. (2010)	Selection of best supplier from three alternatives for a company based on criteria like quality, cost, delivery, equipment, flexibility, documentation and cooperation using AHP.
13	Ebrahimi *et al*. (2018)	Selection of best concrete structures from five alternatives with limited floors in Iran based on criteria like cost, time, applicability and technical characteristics with industrialization approach using AHP.
14	Rao and Davim (2008)	Selection of best material for a non-heat-treatable cylindrical cover material from seven materials considering twelve attributes using AHP and TOPSIS.
15	Karim and Karmaker (2016)	Selection of best machine from three alternatives used in a company considering seven major criteria and numerous sub-criteria using AHP and TOPSIS.
16	Sapun *et al*. (2011)	Selection of best natural fibre from 29 alternatives in making fibre reinforced polymer composites for automotive dashboard panel considering three main criteria: density, young's modulus and tensile strength using AHP.
17	Shi *et al*. (2009)	Improved AHP is made using Fault Tree Analysis and Traditional AHP to evaluate the fire safety of public buildings based on various attributes.
18	Venkata Rao (2008)	Selection of the best Flexible Manufacturing Systems from eight alternatives based on 24 criteria using combined AHP and TOPSIS.
19	Vichare *et al*. (2015)	Selection of the most advantageous plot to real estate project from three alternatives based on three-level criteria system using AHP.
20	Wong and Li (2008)	Selection of best Intelligent Building (IB) products using general survey and AHP. Four major criteria and two sub-criteria are considered in performing AHP.

weights and the options scores, thus determining a global score for each option, and a consequent ranking. The global score for a given option is a weighted sum of the scores it obtained with respect to all the criteria.

AHP is a very flexible and powerful tool. It helps us to set priorities and make the best decision when both tangible and non-tangible aspects of decision need to be considered. It not only helps the decision makers to arrive at the best decision, but also provides a clear rationale that it is the best. This is because it reduces the decisions of complex nature to a series of one-on-one comparisons and then the results are synthesized. Hence AHP is a tool that is able to translate both qualitative and quantitative evaluations into a multi-criteria ranking and is regarded as the most widely used decision making method. Many investigations are undertaken using this AHP process as shown in Table 1.

In this study, bagasse ash blended High Performance Concrete (HPC) is studied. Experiments are conducted to find the various mechanical and durability (criteria) properties on five mix proportions of concrete (alternatives) with 0%, 5%, 10%, 15% and 20% of bagasse ash. These properties are then compared for all the alternatives using AHP and the best alternative is found out.

2. Optimization methodology

The Analytical Hierarchy Process (AHP) is the optimization methodology used in this study. It is a Multi-Criteria Decision Making (MCDM) tool and hence combines all the criteria of all the alternatives into a single value and ranks them in sequence. The AHP is a very flexible and powerful tool, because, the scores, and therefore the final ranking, are obtained on the basis of the pair-wise relative evaluations of both the criteria and the options provided by the user. The computations made by the AHP are always guided by the decision maker's experience, and the AHP can thus be considered as a tool that is able to translate the evaluations (both qualitative and quantitative) made by the decision maker into a multi-criteria ranking. In addition, the AHP is simple because there is no need of building a complex expert system with the decision maker's knowledge embedded in it.

The AHP can be implemented in three simple consecutive steps:

1) Computing the vector of criteria weights,
   - Define the objectives
   - Identify criteria/attributes
   - Select the alternatives
   - Arrange in hierarchical structure the objectives, criteria and alternatives
2) Computing the matrix of option scores, and
3) Ranking the options.

Step 1: Computing the vector of criteria weights

Generating a *pair-wise comparison matrix* **A**is the first step in this process. This is done to find the relative importance of different criteria/sub-criteria with respect to the objective. The matrix **A** shown in Eq. (1) is an $m\times m$ real matrix, where m is the number of evaluation criteria considered. Each entry $a_{jk}$of the matrix **A** represents the importance of the j^{th} criterion relative to the k^{th} criterion. If $a_{jk} > 1$, then the j^{th} criterion is more important than the k^{th} criterion, while if $a_{jk} < 1$, then the j^{th} criterion is less important than the k^{th} criterion. If two criteria have the same importance, then the entry $a_{jk}$is 1. The relative importance between two criteria is measured according to a numerical scale from 1 to 9, as shown in Table 2. Hence, the A matrix is formed using this fundamental scale of AHP.

Hence the pair-wise comparison matrix is generated as follows

$$A=\begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \tag{1}$$

Step 2: Assigning weights for sub-criteria

The normalized weights for the sub-criteria are obtained by Eq. (3) finding the geometric means of each row in A matrix by Eq. (2) and normalizing them. The geometric mean method is usually used to find the relative normalized weights of the criteria/sub-criteria. It is commonly used because of its simplicity, finding the maximum Eigen value with ease and the reduction in the inconsistency in judgments.

Table 2 Nine point scale of Pair-wise comparison by Saaty (1980)

Value of a_{jk}	Interpretation
1	*j* and *k* are equally important
3	*j* is slightly more important than *k*
5	*j* is more important than *k*
7	*j* is strongly more important than *k*
9	*j* is absolutely more important than *k*
2,4,6,8	Intermediate values of relative importance

$$GM_i = \{a_{i1} \times a_{i2} \times \ldots . \times a_{ij}\}^{1/n} \tag{2}$$

$$W_i = \frac{GM_i}{\sum_{j=1}^{j=n} GM_i} \tag{3}$$

Step 3: Forming C matrix

It is defined as the product of pair-wise comparison matrix and the column weight matrix given by Eq. (4). It denotes an n-dimensional column vector describing the sum of the weighted values for the importance degrees of the attributes.

$$C = A.W \tag{4}$$

Step 4: Finding the consistency value

The consistency value is given by Eq. (5).

$$CV_i = \frac{C_i}{w_i} \tag{5}$$

After finding the consistency value, the lambda maximum ($\lambda_{\max}$) which isthe average of the consistency values given by Eq. (6) is found.

$$\lambda_{max} = \frac{\sum_{i=1}^{i=n} CV_i}{n} \tag{6}$$

The use of the maximum Eigen value $\lambda_{\max}$ was suggested by Saaty to calculate the effectiveness of judgment.

Step 5: Finding Consistency Ratio

The consistency ratio (CR) is given by Eq. (7)

$$CR = \frac{CI}{RI} \tag{7}$$

$$CI = \frac{(\lambda_{max} - n)}{n-1} \tag{8}$$

$$RI = \frac{[1.987.(n-2)]}{n} \tag{9}$$

where, *CI* is the consistency index as per Eq. (8) and RI is Random Inconsistency as per Eq. (9). The evaluation of the pair-wise comparison matrix is implied to be perfectly consistent if $CI = 0$. In general closer the value of $\lambda_{\max}$to n, the more consistent is the evaluation. Hence a consistency ratio (CR) is used as a guide to check the consistency.

If the computed CR value is less than 0.1, then the comparison matrix is accepted, or else a new comparison

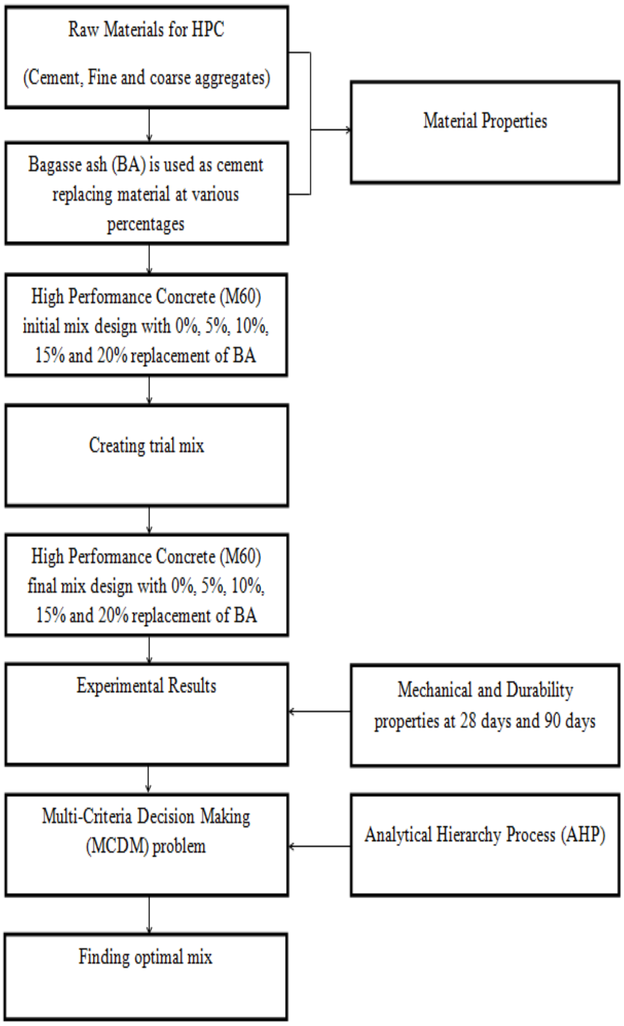


Fig. 1 Methodology framework

matrix is to be constructed.

Step 6: Ranking

The alternatives are then ranked based on overall performance level of each alternative with respect to criteria.

$$P_k = \sum_{i=1}^{i=n} w_i \sum_{j=1}^{j=m} w_{ij} \tag{10}$$

where w_i are the weights of criteria and w_j are the weights of alternatives respectively.

3. Methodology for optimization of bagasse ash blended high performance concrete

The optimal mix design for the Bagasse Ash (BA) blended High Performance Concrete (HPC) is necessary in determining the quality assessment of concrete. Finding the optimal mix design is a Multi-Criteria Decision Making (MCDM) problem since there are various mechanical and durability properties that determine the efficiency of concrete. There are various methods used in finding the optimal mix design, and the proposed method used in this paper is Analytical Hierarchy Process (AHP). The framework of the methodology is shown in Fig. 1.

3.1 Mix proportion

M60 grade HPC is designed as per ACI 211-1 standard practice as proposed by P.C. Aitcin. Five concrete mixes are designed for the experiment. Cement content of 510 kg/m^{3}is used for the control specimen and bagasse ash is replaced at 5%, 10%, 15%, 20% of cement for the remaining mixes. Fine aggregates of 809 kg/m^3 and coarse aggregates of 1125 kg/m^3 are used for all the mixes. The water content of the mix and W/B ratio are 130 kg/m^3 and 0.28. The super plasticizer dosage was 10 lit/m^3. The mixes were designated as BA0 for control specimen and BA1-BA4 for bagasse ash blended high performance. The mix details are shown in Table 3.

3.2 Specimen preparation

Various types of specimens are prepared for conducting different experiments. The specimen details for HPC for the strength and durability properties are shown in Tables 4-5. The test specimen were removed from the moulds after 24 hours from casting and then immersed in water for curing, till the test age.

Various tests are carried out to find the mechanical and durability properties of the HPC at 28 days and 90 days. In total, the values of 17 parameters are found from various experiments. The various parameters and their importance in making the decision for the final optimal mix are shown in Table 6.

3.3 Hierarchical structure

After obtaining the experimental results for each design mix, it is necessary to categorize the goal, alternatives, criteria and sub-criteria to follow the Analytical Hierarchy

Table 3 Mix design

Mix No.	Bagasse Ash (%)	Water Binder ratio	Cement (kg/m^3)	Bagasse Ash (kg/m^3)	Fine aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Super Plasticizer (Litres)	Water (kg/m^3)
BA0	0	0.28	510.00	00.00	809	1125	10	130
BA1	5	0.28	485.85	24.15	809	1125	10	130
BA2	10	0.28	461.70	48.30	809	1125	10	130
BA3	15	0.28	437.55	72.45	809	1125	10	130
BA4	20	0.28	413.4	96.60	809	1125	10	130

Table 4 Specimen details of strength properties

S. No.	Test type	Studied properties (28 days)	Specimen size	No. of samples
1.	Compressive Strength	Cube compressive strength	150 mm cube	15
2.	Splitting Strength	Splitting tensile strength	150 mm× 300 mm cylinder	15
3.	Flexural Strength	Flexural tensile strength (modulus of rupture)	100 mm× 100 mm× 500 mm Prism	15
4.	Modulus of Elasticity	Elastic modulus	150 mm×300 mm cylinder	15
		Total samples		60

Table 5 Specimen details for durability properties

S. No.	Test type	Studied Properties (90 days)	Specimen size	No of samples
1.	Saturated water absorption	% water absorption	100 mm cube	15
2.	Porosity	Porosity	100 mm cube	15
3.	Sorptivity	Sorptivity	100 mm cube	15
4.	Acid Resistance	Acid resistance	100 mm cube	15
5.	Sea water resistance	Sea water resistance	100 mm cube	15
6.	Impact strength	Quality	152 mm×62.5 mm	15
7.	Free drying shrinkage	Shrinkage	25 mm×25 mm×285 mm	15
8.	Alkalinity measurement	pH for HPC	HPC powder	Powder sample
9	Water Penetration	Depth of Penetration	100 mm cube	15
10	Water Permeability	Permeability	100 mm cube	15
		Total samples		135

Table 6 Preference values

S.No.	Notation	Properties	Type of test	Preference	Importance Factor
1	CS	Compressive strength (MPa)	Hardened concrete	Larger is better	Very important
2	SP	Splitting tensile strength(MPa)	Hardened concrete	Larger is better	Very important
3	FS	Flexural strength (MPa)	Hardened concrete	Larger is better	Very important
4	ME	Modulus of elasticity (GPa)	Hardened concrete	Larger is better	Important
5	µ	Poisson’s ratio	Hardened concrete	Larger is better	Important
6	SL	Slump loss (mm)	Fresh concrete	Larger is better	Very less significance
7	AC	Air content (%)	Fresh concrete	Smaller is better	Slightly important
8	SWA	Saturated water absorption (%)	Hardened concrete	Smaller is better	Very important
9	P	Porosity (%)	Hardened concrete	Smaller is better	Slightly important
10	S	Sorptivity (mm/min0.5)	Hardened concrete	Smaller is better	Slightly important
11	pH	Alkalinity measurement	Hardened concrete	Smaller is better	Moderately important
12	IT	Impact strength (N-m)	Hardened concrete	Larger is better	Moderately important
13	DS	Drying shrinkage (mm)	Hardened concrete	Smaller is better	Important
14	SWR	Sea water resistance (%)	Hardened concrete	Larger is better	Important
15	ART	Acid resistance test (%)	Hardened concrete	Larger is better	Important
16	WPC	Water Penetration (%)	Hardened concrete	Smaller is better	Very important
17	WP	Water Permeability ($m/s \times 10^{-12}$)	Hardened concrete	Smaller is better	Very important

Process (AHP) for decision making. The hierarchical structure followed is shown in Fig. 2.

4. Results and discussions

4.1 Experimental results

The tests are conducted at 28 days and 90 days and the mechanical and durability properties of concrete are found out. For selecting the mix design, it is necessary to evaluate the strength/mechanical properties at 28 days and durability properties at 90 days respectively. The results of the mechanical properties at 28 days, and the durability properties at 90 days, are tabulated in Table 7 and Table 8 respectively.

The results of the compressive strength of the control mix and the blended concrete at 28 days are shown in Table 7. The control mix has a compressive strength of 65.2 MPa. It is observed that the mix BA2 showed the maximum increase in compressive strength by 1.5%. Mix BA1 and BA3 had an increase in compressive strength of 0.25% and 0.6% respectively. The mix BA4 showed a decrease in compressive strength by 7.5%. The Splitting Tensile

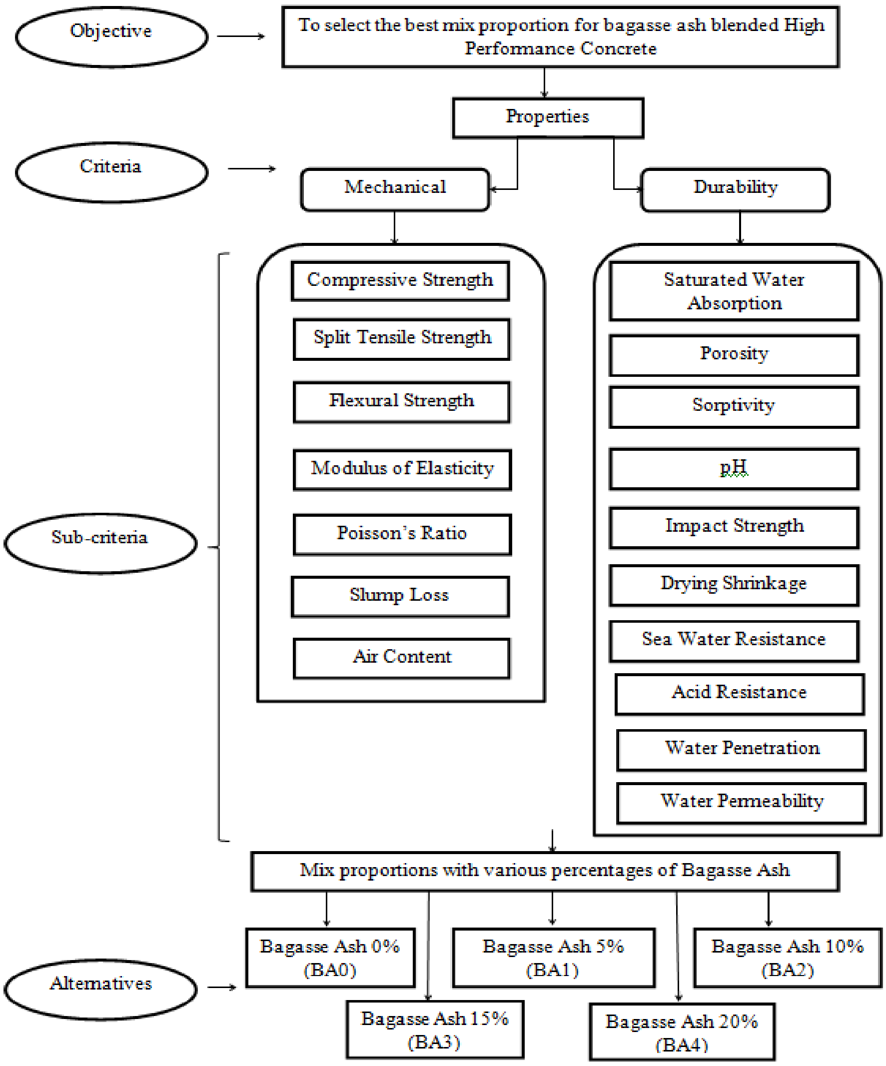


Fig. 2 Hierarchical structure

Table 7 Mechanical properties at 28 Days

Mix No.	CS MPa	SP MPa	FS MPa	ME Gpa	μ	SL mm	AC %
BA0	65.2	4.41	8.12	30.1	0.1245	140	0.6
BA1	65.6	4.98	8.29	30.8	0.1263	145	0.6
BA2	66.2	5.52	8.37	31.7	0.1264	150	1.1
BA3	65.35	4.32	7.52	32.2	0.115	140	2.8
BA4	60.3	3.76	7.3	33.8	0.121	135	3.4

strength results at 28 days for the control mix and blended concrete are shown in Table 7. The strength of the control mix is 4.41 MPa. The mixes BA1 and BA2 showed an increase in strength by 12.93% and 25.17% respectively, whereas the mixes BA3 and BA4 showed a decrease in strength by 2% and 14.74% respectively. The flexural strength of the concrete mixes at 28 days is shown in Table 7. The strength of the control mix is 8.12 Mpa. It is observed that the mixes BA1 and BA2 showed an increase in flexural strength by approximately 3%. The mixes BA3 and BA4 showed a decrease in strength by 7.4% and 10% respectively. The comparison of the three strengths for the five mix proportions is shown in Figs. 3 (a)-(c).

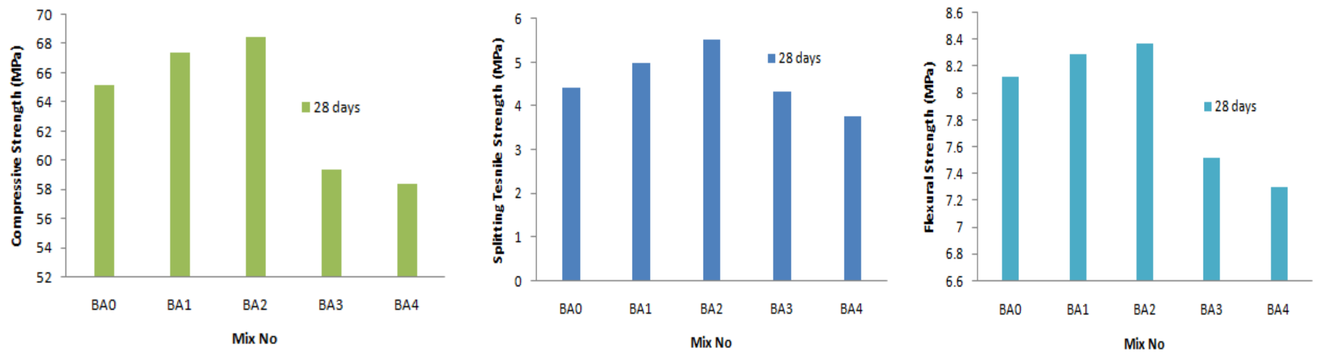
The modulus of elasticity increased with increase in the percentage of bagasse ash. The control mix has an elastic modulus of 30.1 GPa, whereas it increased by 2%, 5%, 7% and 12% for BA1, BA2, BA3 and BA4 respectively. The Poisson's ratio of the control mix is 0.1245. The value increased by 1.5% for BA1 and BA2 mixes and decreased by 8% and 3% for BA3 and BA4 respectively. The variations of these two criteria are shown in Figs. 4(a)-(b).

An increased slump value increases the workability of concrete, and decreased air content is necessary for enhancing the strength of the concrete. The slump value is high for the mix BA2 and hence it has the best workability properties. The air content is 0.6% for the control mix but gradually increased for all the other mixes blended with bagasse ash. Hence, partial replacement of cement with bagasse ash enhances the air content and this may be a factor in reducing the strength properties of the concrete. The variations are shown in Figs. 5 (a)-(b).

The results of the durability properties as enumerated in Table 8 are taken at 90 days for studying the performance of the concrete. The saturated water absorption (SWA) is

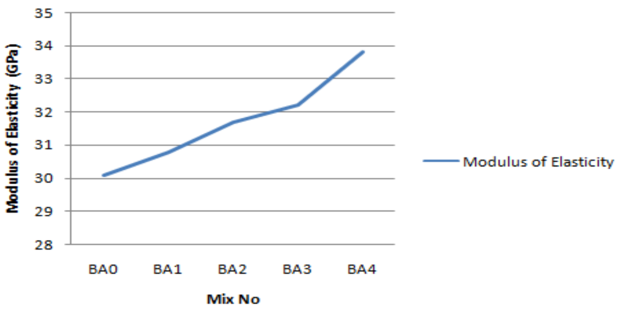
Table 8 Durability properties at 90 Days

Mix No.	SWA %	P %	S mm/min^0.5	pH	IT Nm	DS mm	SWR %	ART %	WPC %	WP m/s ×10^-12
BA0	1.57	2.4	0.0304	13.4	3636	1.25	8.61	7.1	52	8.24
BA1	1.3	2.14	0.0257	12.23	4242	1.11	8.65	6.83	48	7.02
BA2	1.15	1.85	0.0234	13.16	4524	0.95	8.78	5.55	35	3.73
BA3	1.08	2.08	0.0245	13.1	4666	0.76	8.53	5.27	34	3.52
BA4	0.71	2.02	0.0247	13.05	4807	0.66	8.42	5.01	29	2.56

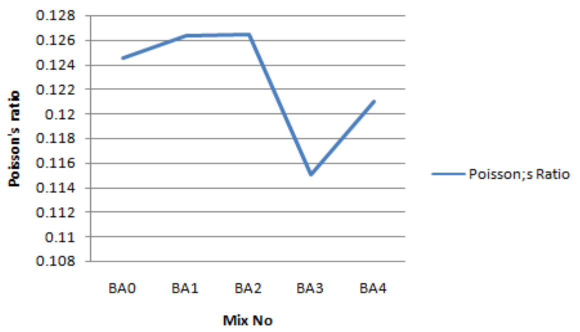


(a) Compressive strength (b) Splitting tensile strength (c) Flexural strength

Fig. 3 Comparison of strengths at 28 days



(a) Modulus of elasticity

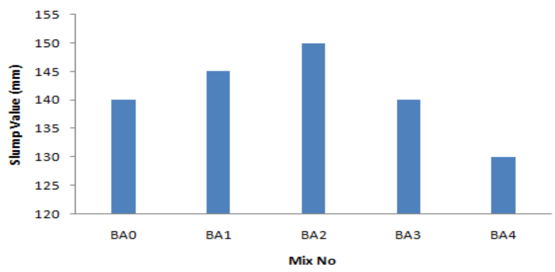


(b) Poisson's ratio

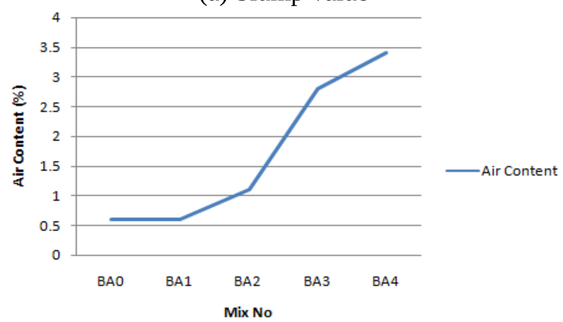
Fig. 4 Variation in modulus of elasticity and Poisson's ratio for various mixes at 28 days

found to be 1.57% for the control mix and 1.3%, 1.15%, 1.08% and 0.71% for the mixes BA1, BA2, BA3 and BA4 respectively. It is observed that the optimum replacement percentage in terms of SWA is 20% of bagasse ash for achieving the lowest value. The variation in SWA is shown in Fig. 6.

The porosity and sorptivity values should also be low for a concrete mix. It is observed that the porosity and



(a) Slump value



(b) Air content

Fig. 5 Variation in slump values and air content for various mixes

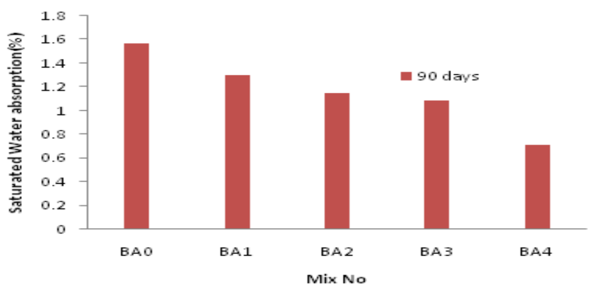
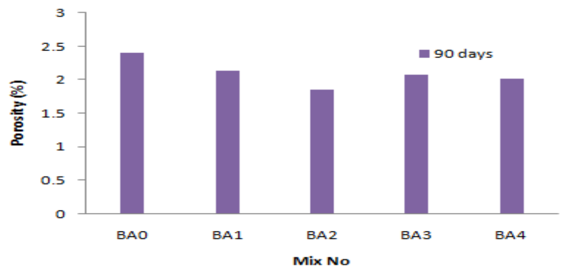
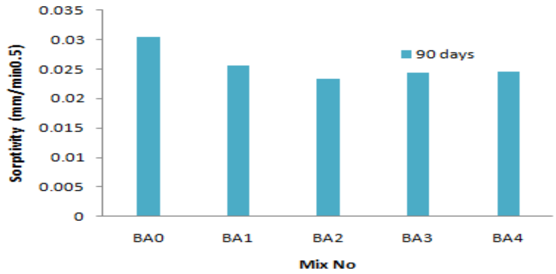


Fig. 6 Variation in Saturated Water Absorption at 90 days

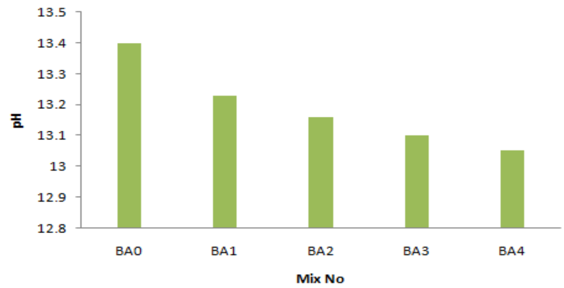


(a) Porosity

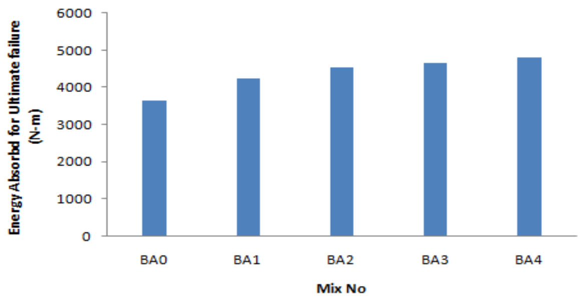


(b) Sorptivity

Fig. 7 Variation of porosity and sorptivity at 90 days



(a) pH



(b) Impact strength

Fig. 8 Variation of pH and impact strength at 90 days

sorptivity of the mix BA2 has the lowest value of 1.85% and 0.0234 mm/min$^{0.5}$ respectively when compared to the control mix with 2.40% and 0.0304 mm/min^0.5 respectively. In general all the blended concrete mixes have low porosity when compared to the control mix. This is because, the pozzolon with fine particle size reduced the porosity by modifying the pore structure of the concrete. It is experiential that the sorptivity of the HPC mixes containing bagasse ash was lesser when compared with that of HPC mixes free from bagasse ash. The reduction in sorptivity varies from 15% to 23% for different bagasse ash blended high performance concrete. The variation of porosity and sorptivity is shown from Figs. 7 (a)-(b).

The performance of the concrete is more when they have high alkaline nature. The concrete mixes containing bagasse howed lesser value of pH as compared to concrete mix without bagasse ash. Hence the impregnation of bagasse ash in concrete reduced the alkalinity by very small amoash sunts. The alkaline nature decreased by 1% to 3% for the various blended mixes with respect to the control concrete. High values of impact resistance indicate high durability of the concrete. It is observed that all the blended concrete mixes show high resistance to impact when compared to the control concrete mix which has an impact resistance of 3636 Nm. The impact resistance of BA1, BA2, BA3 and BA4 increased by 16%, 24%, 28% and 32% respectively. The variation in pH and impact strength is shown in Figs. 8 (a)-(b).

The Sea Water Resistance (SWR) and Acid Resistance (ART) are very useful in finding the durability of concrete structures. The values are denoted in percentage of attack, i.e., lower the value, lower the attack on structures and hence higher the resistance. Both the SWR and ART increase with increase in the percentage of bagasse ash in concrete. Hence the mix BA4 shows the best resistance against acid attack and sea water attack with 8.42% and

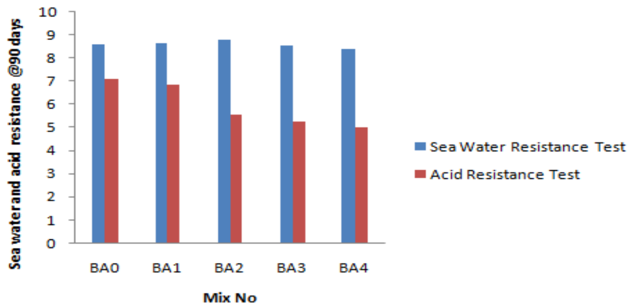


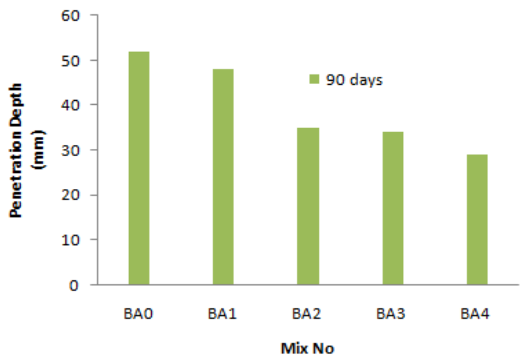
Fig. 9 Variations in SWA and ART at 90 days

5.01% respectively, compared to 8.61% and 7.10% of the control mix. The variations in SWA and ART are shown in Fig. 9.

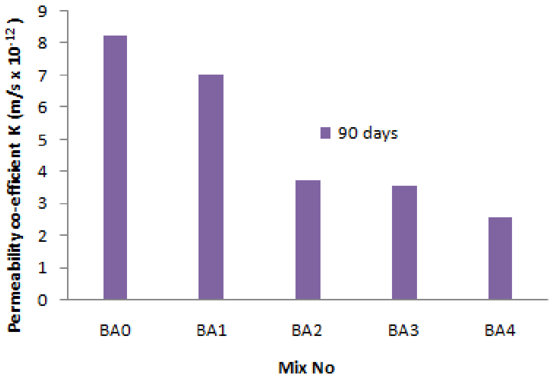
The Water Penetration Test (WPC) and Water Permeability Test (WP) are also indicators of durability in concrete. The lower the penetration and permeability, the higher is the performance of the concrete. It can be seen that the WPC and WP values of the mix BA4 are very less and hence 20% replacement gives the best results. The values for BA4 decreased by a large amount of 80% and 70% for WPC and WP respectively with respect to the control concrete. The variations in WPC and WP are shown in Figs. 10 (a)-(b).

4.2 Generating pair-wise comparison matrix

A pair-wise comparison matrix is created for both mechanical properties and durability properties separately. Before forming this matrix, each main criterion (mechanical and durability) is given a weightage of 0.5 each. The pair-wise comparison matrices for mechanical properties (A_1) and durability properties (A_2) are shown below as per Eq. (1).



(a) Water penetration



(b) Water permeability

Fig. 10 Variation in WPC and WP at 90 days

$$A_1 = \begin{array}{c} \begin{array}{ccccccc} CS & SP & FS & ME & \mu & SL & AC \end{array} \\ \begin{bmatrix} 1 & 1 & 1 & 3 & 3 & 9 & 6 \\ 1 & 1 & 1 & 3 & 3 & 9 & 6 \\ 1 & 1 & 1 & 3 & 3 & 9 & 6 \\ 1/3 & 1/3 & 1/3 & 1 & 1 & 7 & 4 \\ 1/3 & 1/3 & 1/3 & 1 & 1 & 7 & 4 \\ 1/9 & 1/9 & 1/9 & 1/7 & 1/7 & 1 & 1/3 \\ 1/6 & 1/6 & 1/6 & 1/4 & 1/4 & 3 & 1 \end{bmatrix} \end{array} \begin{array}{c} CS \\ SP \\ FS \\ ME \\ \mu \\ SL \\ AC \end{array}$$

$$A_2 = \begin{array}{c} \begin{array}{cccccccccc} SWA & P & S & pH & IT & DS & SWR & ART & WPC & WP \end{array} \\ \begin{bmatrix} 1 & 7 & 7 & 5 & 5 & 2 & 3 & 3 & 1 & 1 \\ 1/7 & 1 & 1 & 1/4 & 1/4 & 1/7 & 1/7 & 1/7 & 1/7 & 1/7 \\ 1/7 & 1 & 1 & 1/4 & 1/4 & 1/7 & 1/7 & 1/7 & 1/7 & 1/7 \\ 1/5 & 4 & 4 & 1 & 1/2 & 1/5 & 1/3 & 1/3 & 1/5 & 1/5 \\ 1/5 & 4 & 4 & 2 & 1 & 1/5 & 1/3 & 1/3 & 1/5 & 1/5 \\ 1/2 & 7 & 7 & 5 & 5 & 1 & 2 & 2 & 1/5 & 1/2 \\ 1/3 & 7 & 7 & 3 & 3 & 1/2 & 1 & 1 & 1/3 & 1/3 \\ 1/3 & 7 & 7 & 3 & 3 & 1/2 & 1 & 1 & 1/3 & 1/3 \\ 1 & 7 & 7 & 5 & 5 & 2 & 3 & 3 & 1 & 1 \\ 1 & 7 & 7 & 5 & 5 & 2 & 3 & 3 & 1 & 1 \end{bmatrix} \end{array} \begin{array}{c} SWA \\ P \\ S \\ pH \\ IT \\ DS \\ SWR \\ ART \\ WPC \\ WP \end{array}$$

The matrices A_1 and A_2 are formed based on the preference values in Table 3. In matrix A_1 it can be seen that SP and FS are equally important as CS. Hence a relative importance value of 1 is assigned to CS over SP and FS (i.e., $a_{12} = a_{13} = 1$)and a relative importance value of 1/1 is assigned to SP and FS over CS (i.e., $a_{21} = a_{31} = 1/1$). CS, SP and FS are slightly more important than ME andμ. Hence a relative importance value of 3 is given to CS, SP and FS over ME and μ (i.e., $a_{14} = a_{15} = a_{24} = a_{25} = 3$) and a relative importance value of 1/3 is given to ME and μ over CS, SP and FS (i.e., $a_{41} = a_{51} = a_{42} = a_{52} = 1/3$).

Table 9 Values for consistency ratio

Parameter	Mechanical Criteria	Durability Criteria
λ_{max}	7.175623783	10.49971727
Consistency Index (C.I)	0.02927063	0.055524141
Random Inconsistency (R.I)	1.419285714	1.5896
Consistency Ratio (C.R)	0.020623494	0.034929631

In matrix A_2 it can be seen that SWA is strongly more important than P and S. Hence a relative importance of 7 is assigned to SWA over P and S (i.e., $a_{12} = a_{13} = 7$) and a relative importance of 1/7 is assigned to P and S over SWA (i.e., $a_{21} = a_{31} = 1/7$). Similarly, the relative importance among all the parameters can be explained and the matrices A_1 and A_2 are formed.

4.3 Sub-criteria weights

The weights are assigned as per Eq. (3). The geometric average for both the mechanical and durability properties are found from the pair-wise comparison matrix as per Eq. (2). From this, the weights of the mechanical sub-criteria $W_1$and durability sub-criteria$W_2$are found out, and they are enlisted in matrices below.

$$W_1 = \begin{pmatrix} 0.2465 \\ 0.2465 \\ 0.2465 \\ 0.1019 \\ 0.1019 \\ 0.0193 \\ 0.0372 \end{pmatrix} \quad W_2 = \begin{pmatrix} 0.1928 \\ 0.0166 \\ 0.0166 \\ 0.0367 \\ 0.0422 \\ 0.134 \\ 0.0872 \\ 0.0872 \\ 0.1928 \\ 0.1928 \end{pmatrix}$$

4.4 Finding consistency ratio

The consistency ratio (CR) is given by Eq. (7). The various parameters for finding the consistency ratio like C-matrix (Eq. (4)), Consistency value (Eq. (5)),λ_{max} (Eq. (6)), Random Inconsistency (Eq. (9)) and Consistency Index (Eq. (8)) are found out separately for both mechanical and durability sub-criteria. The values are enlisted in Table 9.

It is found that the consistency ratios for both mechanical criteria (0.0206) and durability criteria (0.0349) are less than 0.1 and hence the assigned weights are acceptable.

4.5 Final weights and ranking

The final weights for all the 17 parameters are then found by multiplying the weights of each sub-criterion by 0.5, since the weights of the main criteria are equally divided. The final weights of the mechanical and durability sub-criteria are enlisted in Tables 10-11.

After finding the final weights, the normalized weights of each sub-criterion are found for all the five alternatives and enlisted in Tables 12-13.The normalized weights are

Table 10 Final weights for mechanical properties

Mechanical Sub Criteria	
[0.5]	
CS	0.123253071
SP	0.123253071
FS	0.123253071
ME	0.050977468
μ	0.050977468
Slump	0.009664376
AC	0.018621476

Table 11 Final weights for durability properties

Durability Sub Criteria	
[0.5]	
SWA	0.096412687
P	0.008332097
S	0.008332097
pH	0.018374567
IT	0.021106835
DS	0.0673758
SWR	0.043620272
ART	0.043620272
WPC	0.096412687
WP	0.096412687

Table 12 Normalized Weights (N.W) of mechanical properties

Alternatives /Criteria	CS	SP	FS	ME	*μ*	SL	AC
BA0	0.202	0.191	0.205	0.189	0.203	0.197	0.340
BA1	0.203	0.216	0.209	0.194	0.205	0.204	0.340
BA2	0.205	0.240	0.211	0.199	0.206	0.211	0.185
BA3	0.202	0.187	0.189	0.203	0.187	0.197	0.072
BA4	0.186	0.163	0.184	0.213	0.197	0.190	0.060

found based on the preference values shown in Table 6. In order to find the normalized values for a single parameter, experimental results are compared for all the alternatives with each other. It is done in a similar way of forming the pair-wise comparison matrix as shown in Eq. (1)

For example, the normalized matrices for compressive strength (B_1) and Saturated Water Absorption (B_2) are shown below.

$$B_1 = \begin{array}{c} \begin{array}{ccccc} BA0 & BA1 & BA2 & BA3 & BA4 \end{array} \\ \begin{bmatrix} 1 & 0.994 & 0.985 & 0.998 & 1.081 \\ 1.006 & 1 & 0.991 & 1.004 & 1.088 \\ 1.015 & 1.009 & 1 & 1.013 & 1.098 \\ 1.002 & 0.996 & 0.987 & 1 & 1.084 \\ 0.925 & 0.919 & 0.911 & 0.923 & 1 \end{bmatrix} \end{array} \begin{array}{c} \\ BA0 \\ BA1 \\ BA2 \\ BA3 \\ BA4 \end{array}$$

$$B_2 = \begin{array}{c} \begin{array}{ccccc} BA0 & BA1 & BA2 & BA3 & BA4 \end{array} \\ \begin{bmatrix} 1 & 0.828 & 0.732 & 0.688 & 0.452 \\ 1.208 & 1 & 0.885 & 0.831 & 0.546 \\ 1.265 & 1.130 & 1 & 0.939 & 0.617 \\ 1.454 & 1.204 & 1.065 & 1 & 0.657 \\ 2.211 & 1.831 & 1.620 & 1.521 & 1 \end{bmatrix} \end{array} \begin{array}{c} \\ BA0 \\ BA1 \\ BA2 \\ BA3 \\ BA4 \end{array}$$

For compressive strength (CS) larger values are preferred. Hence, the matrix B_1 is obtained by comparing the results of BA0 over BA0, BA1, BA2, BA3 and BA4; BA1 over BA0, BA1, BA2, BA3 and BA4 and similarly for other alternatives. Hence, a_{11}=BA0/BA0, a_{12}=BA0/BA1, a_{13}=BA0/BA2 and so on. Similarly, a_{21}=BA1/BA0, a_{22}=BA1/BA1, a_{23}=BA1/BA2 are calculated. In this way all the five rows are filled. After finding the matrix B_1, the Geometric mean (G.M) for each row/alternative is found. The normalized weights (N.W) are finally obtained by dividing G.M of one alternative by the sum of the G.Ms (i.e., $N.W_x = \frac{G.M}{\sum_{x=BA0}^{x=BA4} G.Mx,}$).

For Saturated Water Absorption (SWA) smaller values are preferred. Hence the matrix B_2 is obtained by comparing the results of BA0, BA1, BA2, BA3 and BA4 over BA0; BA0, BA1, BA2, BA3 and BA4 over BA1 and similarly for other alternatives (Hruska *et al*. 2014). Hence a_{11}=BA0/BA0, a_{12}=BA1/BA0, a_{13}=BA2/BA0 and so on. Similarly, a_{21}=BA0/BA1, a_{22}=BA1/BA1, a_{23}=BA2/BA1 are calculated. After finding B_2, the same procedure is followed to find the normalized weights (N.W) for each alternative as mentioned for compressive strength.

The final score of the alternatives is then found by Eq. (10) and the alternatives are ranked, as shown in Table 14.
Table 10Final Weights for Mechanical Properties

5. Conclusions

The following conclusions were drawn from experimental and optimization technique:

- Inclusion of bagasse ash improves strength properties of concrete up to 10%. Bagasse ash acts as micro filler and improves the density of cement paste. Therefore, the bond between the cement paste and the aggregate particles is enhanced and improves the concrete

Table 14 Ranking of alternatives

Alternative	Bagasse Ash percentage (%)	Final Score	Rank
BA4	20	0.221484869	1
BA2	10	0.209050446	2
BA3	15	0.202033189	3
BA1	5	0.189388568	4
BA0	0	0.178042928	5

Table 13 Normalized weights of durability properties

Alternatives/ Criteria	SWA	P	S	pH	IT	DS	SWR	ART	WPC	WP
BA0	0.138	0.173	0.168	0.206	0.166	0.143	0.2002	0.238	0.145	0.100
BA1	0.166	0.194	0.198	0.188	0.193	0.161	0.201	0.229	0.157	0.118
BA2	0.188	0.225	0.218	0.202	0.206	0.188	0.204	0.186	0.215	0.222
BA3	0.200	0.200	0.208	0.201	0.213	0.235	0.198	0.177	0.221	0.235
BA4	0.3052	0.206	0.206	0.2009	0.219	0.271	0.195	0.168	0.260	0.323

strength,

• Durability properties of HPC mixes blended with bagasse ash shows significant improvement between 10% and 15% of replacement of cement,

• Impact resistance of bagasse ash blended HPC mixes showed higher values compared to that of mixes without bagasse ash,

• pH values of powder sample blended with bagasse ash showed lower value compared to sample without bagasse ash, where there is no loss of alkalinity significantly,

• Increase in percentage of bagasse ash resist the sea water and acid attack in high performance concrete and also reduces the water penetration due to the effect of pores structure in bagasse ash blended high performance concrete,

• From the alternatives score obtained using AHP method, the alternatives are ranked as **BA4>BA2>BA3>BA1>BA0,** and

• BA4 mix proportion has the highest value as 0.22148. Hence BA4 is the optimal mix proportions which contains 20% bagasse ash (48.30 kg/m^3) with cement 461.70 kg/m^3, fine aggregate 809 kg/m^3, coarse aggregate 1125 kg/m^3, super plasticizer 10 liters and water 130 kg/m^3 .

Hence, AHP is a very effective method in determining a problem like choosing the best optimal mix, which involves various parameters for ranking.

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