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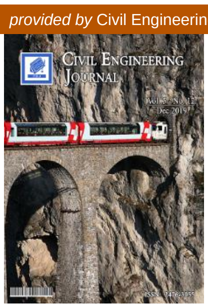
Civil Engineering Journal

Vol. 5, No. 12, December, 2019



A Quantitative Approach to Prioritize Sustainable Concrete

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Received 21 July 2019; Accepted 29 October 2019

Abstract

Cement industry consumes high energy and produces major emissions to the environment. In order to reduce the effects (environmental impact, energy, and resources) caused by conventional materials, various by-products and pozzolonic material are used to achieve sustainable concrete. Assessing the concrete performance based on multiple conflicting attributes is decisive and compelling. It is difficult to choose an alternative among the Supplementary Cementitious Materials (SCM) considering a set of quantitative performance attributes. Hence, the present study utilizes the theories of decision making to prioritize an alternative environmentally and technologically. The purpose of the present study is to observe the sustainable performance of five different concretes made of OPC, Fly ash, GGBS, Metakaolin and Composite Cement for a particular grade of concrete. The study has considered workability, strength attribute (compressive strength, split tensile and flexural strength) and durability attribute (Sorptivity and RCPT) at their respective optimum replacements. To prioritize an alternative material considering quantitative attributes, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is utilized. From the results, it is observed that considering all attributes, flyash based concrete has higher performance and is prioritized among others. The developed approach facilitates the decision-makers in the selection of a sustainable alternative.

Keywords: Sustainable Concrete; Supplementary Cementitious Material; Multi-Criteria Decision Method; Environment; TOPSIS.

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1. Introduction

In developing countries like India, the population is increasing at an asymptotic rate, thus there is a demand for all types of infrastructure facilities. The building industry is growing at a faster rate by consuming the major natural resources resulting in higher carbon footprint [1]. India is the fourth-largest emitter of CO_2, where the major contributor of it is the energy sector with the construction industry being a subset of it [2]. Thus, there is an urgent need to shift our thoughts towards sustainability. To attain sustainability in the construction industry, materials play a crucial part. Selection of suitable material which serves the purpose of the application without degrading the environment leads to sustainable construction. Currently, the construction industry is utilizing industrial by-products and waste materials to decrease the potential impact on natural/non-renewable resources [3]. Choosing appropriate material at the design stage will facilitate to reduce the impacts on the environment [4]. Selection of suitable sustainable material for construction will minimize the impacts, energy consumption and waste production. This will also increase the potential utility for future generations [5]. Therefore, by implementing the principles of sustainability in the construction industry by neglecting conventional practices will certainly achieve an ecological balance between future and present requirements [6].

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http://dx.doi.org/10.28991/cej-2019-03091434

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According to the United Nations, World Commission on Environment and Development has defined sustainable development as “development which meets the needs of present generations without compromising the ability of future generations to meet their own needs” [7] .Furthermore, the influence of materials is observed not only on the environment but also on social and economic aspects [8, 9]. Assessing the material performance to choose the right/appropriate material for achieving sustainability is a crucial aspect in subjectivity. Evaluating the material performance based on one or two parameters and selecting it is not beneficial [10]. Assessment based on a combination of conflicting attributes and constructive attributive is desirable. Although most of the studies concluded that the characteristic performance of a material based on physical, mechanical and durability properties individually [11, 12]. Different materials may perform differently with respect to a single attribute. To choose an optimal material and achieve the desired results, the requirements should be robust enough to achieve the required performance. For example, in the case of concrete, the cost should be reasonable, should be durable and also obey sustainable design principles.

Concrete is the second maximum consumed material next to the water. It is expected that the demand for concrete will rise up to 16 billion ton per year by 2050 [13]. The use of concrete cannot be avoided due to its unique features and advantages, but the impacts caused by concrete can be reduced by producing concrete by focusing more on sustainable aspects like the use of right materials, methods, and technologies [14, 15]. In the recent past literature, most of the researchers are using by-products like Fly ash, Ground Granulated Blast Furnace Slag, Metakaolin, Silica fume, Risk Husk Ash and Composite Cement, etc., in the place of conventional cement material [12, 13]. Thus a situation has arisen, where the selection of suitable cementitious material based on the combined effect of workability, strength, design performance and cost has become difficult. The use of the decision-making theories thus facilitates to prioritize the best sustainable material. Most of the studies proposed various methods in the literature based on the Multi-Criterion Decision Making (MCDM) theories [14, 15]. Every method has its own limitation and applicability on the decision problem. Different applications need different types of concretes, but it is a challenge to decrease the cement content to reduce the environmental effect of them [19, 20]. However, selecting suitable materials for the design of concrete involves various attributes like physical properties, workability, strength, environmental performance, fire resistance, durability aspects, cost, etc., has to be considered concurrently instead of considering only single attribute at a time. In addition, a single attribute cannot judge the performance of concrete with distinctive properties and satisfy the desired properties. To evaluate any material performance, it is necessary to frame a set of significance attribute/criteria. Most of the studies have considered environmental and economic aspects related attributes and none of them talks about the technical aspects and assess the quantitative concrete sustainability [13]. In the present study, an attempt is been made to integrate Workability (W), Compressive Strength (CS), Split Strength (SS), Flexural Strength (FS), Sorptivity (S), Rapid Chloride Penetration Test (RCPT) and Life Cycle Cost (LCC) of a particular grade of concrete in prioritising sustainable material alternative. It is difficult to prioritize the mixes considering various test results developed from various percentage replacements. Hence, the objective of the study is to evaluate the sustainable performance of five different Supplementary Cementitious Material (SCM) including OPC, Fly ash based PPC, Slag based PPC, Metakaolin and Composite Cement using Technique for Order Preference by Similarly to Ideal Solution (TOPSIS) at their respective optimum replacement levels.

2. Research Methodology

Selection of the best material considering several parameters makes the material selection complex and tedious problem [21]. Multiple attributes and material alternatives made the present study to utilize the MCDM technique in selecting the material alternative. A framework has been developed to choose the best binder material considering nine quantitative attributes for achieving sustainable concrete utilizing the TOPSIS method. The five binder material alternatives like Ordinary Portland Cement (OPC), Fly ash (PPC- F), GGBS (PPC- S), Metakaolin (M), and Composite Cement (CC) are considered in producing M20 grade of concrete with 0, 20, 20, 10 and 100% replacement respectively. Figure 1 shows the methodology in carrying the material selection using the TOPSIS method with respect to the decision problem. As the sustainability and durability go hand in hand, it is vital to consider durability aspects in assessing the quantitative performance of concrete along with strength parameters, the basic durability aspect for any type of concrete is related to water absorption through capillary action i.e. Sorptivity. Similarly, the concrete deterioration due to chloride ingression is another importance aspects of durability. The present study considered nine attributes pertaining to fresh properties of concrete, hardened mechanical properties and durability aspects stated as, Workability (W), Compressive strength (CS) for 28, 56 and 90 days, Split tensile (SS) Flexural Strength (FS), Sorptivity (SR), Rapid Chloride Penetration Test (RCPT) and Life Cycle Cost (LCC) in evaluating the quantitative performance of a concrete. Based on the applicability of concrete, the concrete durability aspects are selected. The sorptivity and RCPT is performed to observe the durability performance involved with various SCM’s at their optimum replacement levels for M20 grade of concrete. The fineness of material alternatives OPC, PPC –F, PPC- S, M and CC are found to be less than 10% by weight of material and specific gravities are observed to be 3.05, 2.14, 2.65, 2.96, and 2.86 respectively.

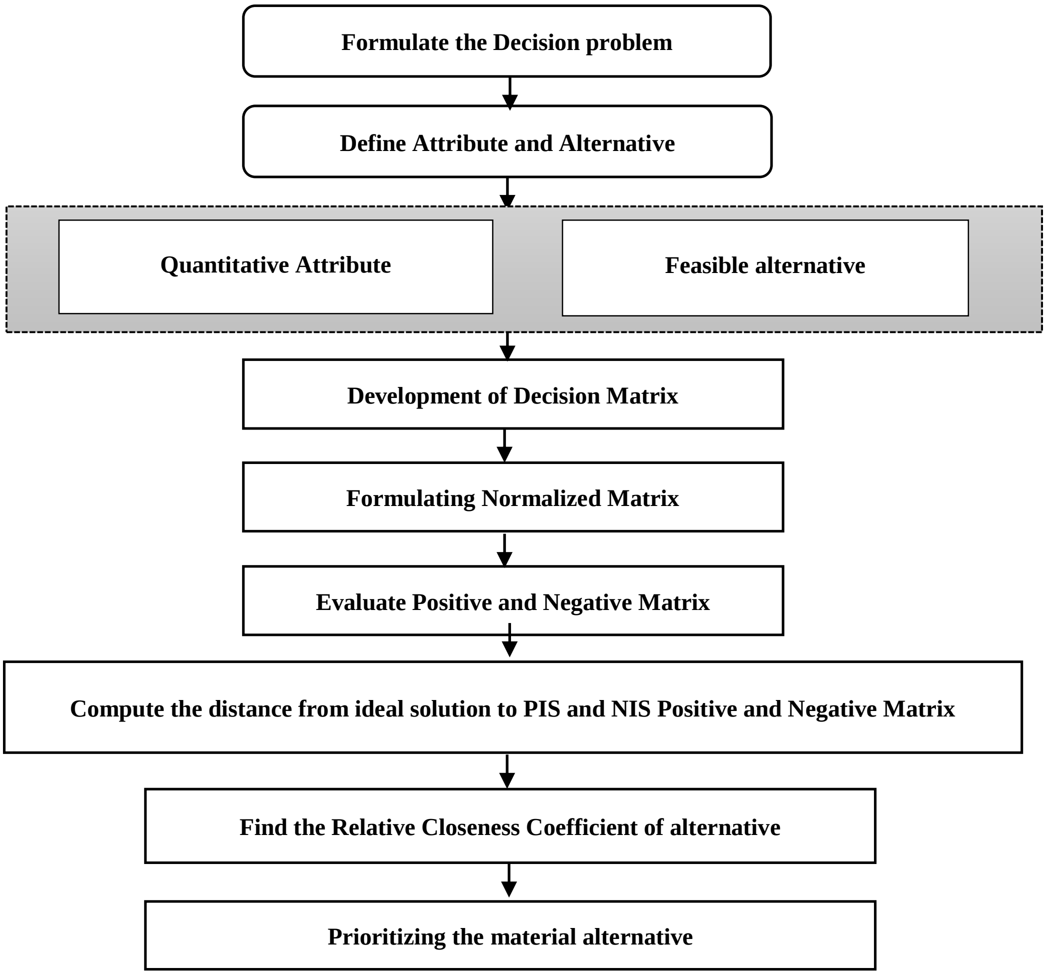

Figure 1. Methodology in selecting sustainable material using TOPSIS

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is used to calculate the relative closeness of alternative solution with the positive and negative ideal solution. It is most widely used MCDM which works on the principles of finding the optimized solution considering conflicting criteria[22]. In the TOPSIS method, the selection of material is based on the attributes having equal importance. However, the weight to attributes can be evaluated using other MCDM techniques and integrate with the TOPSIS method in selecting the best alternative[23]. The present study explores the concept of TOPSIS technique in selecting sustainable building material considering nine quantitative attributes. The following steps are involved in evaluating the best alternative.

Step 1: Creating the decision matrix with ‘p’ number of criteria and ‘q’ number of alternatives. The performance of i^{th}alternative with regard to the $j^{th}$is expressed as x_{ij} and the matrix is formed as shown below:

$$[d_{ij}]_{mxn} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & .. & x_{2n} \\ \vdots & .. & .. & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

Step 2: Normalize the decision matrix to obtain non-dimensional values. The normalized matrix N_{ij} is obtained by the Equation 1.

$$A_{ij} = [a_{ij}]_{mxn} = \frac{x_{ij}}{\sqrt{\sum_1^p x_{ij}^2}} \tag{1}$$

Then the normalized matrix would be $A_{ij} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & .. & a_{2n} \\ \vdots & .. & .. & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}$

Step 3: Evaluate the Positive Ideal Solution (PIS) $A_{ij}^{+}$and Negative Ideal Solution (NIS) A_{ij}^{-} by the Equations 2a and 2b;

$$A_j^+ = (A_1^+, A_2^+, A_3^+ \ldots\ldots A_n^+) = \begin{cases} Max a_{ij} \forall j \in k \\ Min a_{ij} \forall j \in k' \end{cases} \tag{2a}$$

$$A_j^- = (A_1^-, A_2^-, A_3^- \ldots\ldots A_n^-) = \begin{cases} Min a_{ij} \forall j \in k \\ Max a_{ij} \forall j \in k' \end{cases} \tag{2b}$$

Where k is a set of benefit attribute whereas k' is a set of cost attribute.

Step 4: Compute distance between target ideal solution to PIS (D^+) and target ideal to NIS (D^-) by Equation 3a and 3b;

$$D_i^+ = \sqrt{\left\{\sum_{j=1}^{n} \left(A_{ij} - A_j^+\right)\right\}} \forall j \in n;\ \forall i \in m \tag{3a}$$

$$D_i^- = \sqrt{\left\{\sum_{j=1}^{n} \left(A_{ij} - A_j^-\right)\right\}} \forall j \in n;\ \forall i \in m \tag{3b}$$

Step 5: Calculate the Relative Closeness Coefficient (CC) for each alternative from the ideal solution from Equation 4. Higher the closeness coefficient, better is the material sustainability.

$$CC_i = \left\{\frac{D_j^+}{D_j^+ + D_j^-}\right\} \tag{4}$$

3. Results and Discussion

The study used the TOPSIS approach to the decision problem of selecting the best binder material alternative considering nine parameters. The findings of the study optimized the positive attributes and minimized negative attributes.The study considered a fresh property like Workability (W), hardened mechanical properties like Compressive Strength (CS) with respect to the age of curing for 28, 56 and 90 days, Split tensile (SS) Flexural Strength (FS), durability properties like Sorptivity (SR), RCPT and LCC. In the present study, the prevailing rates of material, labor and transportation,and manufacturing in South India have been considered. The Tables (1 – 6) illustrate the results of the TOPSIS method. The results obtained from experimental investigation for nine properties of the concrete made of different SCM's is considered has a decision matrix and are shown in Table 1. Based on the step by step approach described in section 4 the decision problem has been resolved for selecting a best binder material alternative.

Step 1: Formulate the decision matrix considering attributes and alternative. The present study considered nine attributes and five alternatives (Table 1).

Table 1. Decision Matrix for attributes and alternatives

	Attributes								
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
	W (mm)	**CS (MPa)**			**SS (MPa)**	**FS (MPa)**	**SR (mm/ min$^{0.5}$)**	**RCPT (Coulombs)**	**LCC (Rs/cum)**
		28 Days	**56 Days**	**90 Days**	**28 Days**	**28 Days**			
A1	97	25.20	30.08	31.39	2.15	5.96	0.458	2100	9650
A2	100	28.34	30.52	31.16	2.08	4.81	0.342	1248	8350
A3	90	27.23	34.88	37.49	2.56	5.92	0.468	1648	8950
A4	85	26.16	32.70	35.06	1.52	4.82	0.621	1356	9129
A5	92	28.34	30.08	34.88	2.49	6.41	0.547	1895	8432

A1-Ordinary Portland Cement (OPC), **A2**- Pozzolona Portland Cement Flyash based (PPC-F), **A3**- Pozzolona Portland Cement Slag based (PPC-S), **A4**- Metakaolin (M), **A5**- Composite Cement (CC).

Step 2: Normalizing the decision matrix to a non-dimensional unit matrix. The normalization technique is carried out using Equation 1 and represented in Table 2.

Table 2. Normalized Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9
A1	0.47	0.42	0.42	0.41	0.44	0.47	0.41	0.58	0.48
A2	0.48	0.47	0.43	0.41	0.42	0.38	0.31	0.33	0.42
A3	0.43	0.45	0.49	0.49	0.52	0.47	0.42	0.43	0.45
A4	0.41	0.43	0.46	0.46	0.31	0.38	0.56	0.36	0.46
A5	0.44	0.47	0.42	0.46	0.51	0.51	0.49	0.50	0.42

Step 3: The Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) is evaluated using the Equations (2a and 2b) and are represented in Figure 2. The study observed that the attributes W, CS, SS and FS are to be maximized (beneficial attributes) and SR, RCPT, and LCC are minimized (cost attributes).

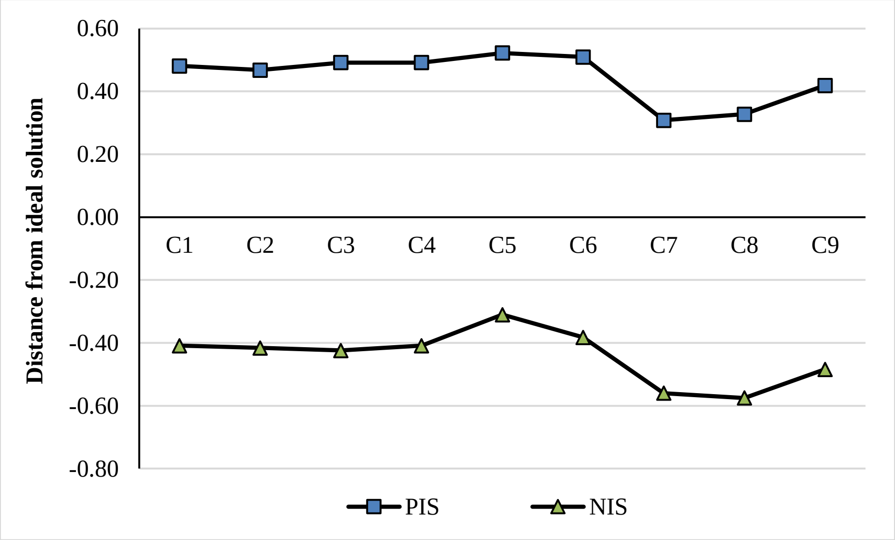

Figure 2. Positive and Negative Ideal Solution with respect to attributes

Step 4: Computethe distance between the target ideal solution to PIS (D^+) and target ideal to NIS (D^-) by Equation (3a and 3b) as shown in Table 3.

Table 3. Distance to PIS and NIS from Ideal Solution is computed using Equations 3a and 3b

	A1	A2	A3	A4	A5
D_i^+	0.31	0.19	0.17	0.37	0.27
D_i^-	0.22	0.39	0.33	0.23	0.28

Step 5: Compute the Closeness Coefficient of each alternative with respect to PIS and NIS using Equation 4 and the findings are represented in Table 4. Higher the Closeness Coefficient (CC) better is the material performance. The findings of the study reveal that the positive and negative values for each attribute will either be converging or diverging towards the ideal solution line (auxiliary zero line) (Figure 2). For example, the criteria Compressive Strength (CS) should be maximized, which is a positive aspect for any alternative, and negatively it should be minimized. Similarly, criteria sorptivity (C7) should be minimized, which is a positive aspect for any alternative and negatively it should be maximized. In the case of criteria C7, the positive and negative values are diverging and for criteria CS, it is observed to be converging towards the ideal solution. The ideal solution (Alternative) is selected based on criteria nearest distance to Positive Ideal Solution (PIS) and farthest Negative Ideal Solution (NIS). Considering equal importance to criteria, from Figure 3, it can be observed that the material alternative (A2) PPC flyash based (PPC-F) is having nearest PIS and farthest NIS. The order of preference for selecting the sustainable binder material alternative based on CC values and is found to be A2 > A3 > A5 > A1 > A4 (Table 4).

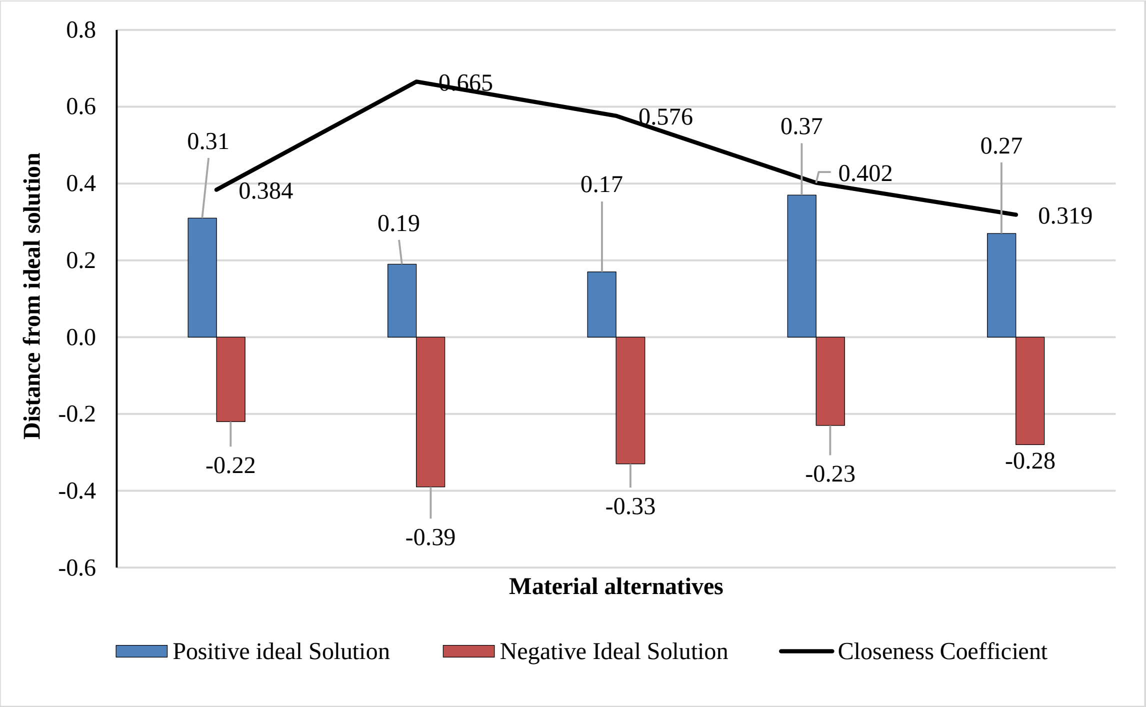

Figure 3. Closeness coefficient and distance from ideal solution for binder alternatives

Table 4. Closeness Coefficient and Prioritizing of Material Alternative

Alternative	**OPC (A1)**	**PPC- Fly ash (A2)**	**PPC-GGBS (A3)**	**Metakaolin (A4)**	**Composite Cement (A5)**
Closeness Coefficient	0.42	0.67	0.66	0.38	0.51
Ranking	4	1	2	5	3

4. Conclusions

The present study explored the use of decision-making method TOPSIS in selecting the best sustainable alternative considering quantitative attribute (Technological aspect).

The study has considered nine quantitative attributes, fresh property- Workability, hardened property- Compressive Strength (28, 56 and 90days), Split tensile and Flexural Strength, durability property - Sorptivity, RCPT and Life Cycle Cost (LCC) in prioritizing the best sustainable material alternative.The following conclusions were drawn for selection of the best sustainable alternative.

- The study has considered nine quantitative attributes i.e., Workability, Strength (28, 56, 90) days, split tensile, Flexural strength, Sorptivity, RCPT and Lifecycle cost for selecting the best alternative.
- Amongst five SCM's, flyash based PPC is prioritized with the highest closeness coefficient of 0.67 whereas Metakaolin has achieved the leastvalue of 0.38.
- The order of priority for selection of sustainable binder material alternative is found to be Flyash based PPC, Slag based PPC, Composite cement, OPC and Metakaolin.
- The approach explored in the study will facilitate the designers to take decisions in selecting the best sustainable material among a pool of available alternatives

5. Acknowledgements

The authors would sincerely like to thank the management of Kakatiya Institute of Technology (KITSW-Autonomous), Warangal, Telangana, Warangal for providing the testing facilities and their constant support.

6. Conflicts of Interest

The authors declare no conflict of interest.

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