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Finding a greener, cost-effective and colour-based partial or complete replacement to White Portland Cement for cast stone production using TOPSIS

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Abstract. As per recent research, the use of White Portland Cement (WPC) in the production of cast stone results in significant carbon emissions. This study aims to identify alternatives to WPC that have lower carbon emissions and are cost-effective. A literature review was performed, and data was gathered on WPC and its alternatives. Based on the literature review, five alternatives were identified. An investigation was conducted to determine the most suitable replacement for WPC based on four criteria. Automatically weighted TOPSIS which is a Multi-Criteria Decision Analysis (MCDA) was used to identify the optimal substitute for WPC. The results of the analysis were used to make a final recommendation. Overall, this study provides valuable insights into the potential substitutes for WPC in the production of cast stone, which could help to reduce carbon emissions and promote greater sustainability in the construction industry.

Keywords: White Portland Cement, Multi-Criteria Decision Analysis, Cast stone, Alternative

1 Introduction

Cement is the most manufactured product on the earth in the 21st century by mass and it is the second highest consumed after water. Cement is used in all the major architectural construction works such as bridges, dams, skyscrapers and roads [1]. Cement is also a raw material for cast stone which is manufactured from a mixture of sand, cement, admixtures and limestone in a fixed proportion to replicate the natural stone [4]. Various garden ornaments and architectural features are made from cast stone.

There are different types of cement such as Ordinary Portland Cement (OPC), Low Heat cement, rapid hardening cement and White Portland Cement (WPC) which are used based on the requirements [2]. Portland cement is the most used type of cement, and it is produced by combining clinker with gypsum [1]. To create the clinker, limestone and specific silicate aggregates are burned at a temperature just above 1500°C in a rotary kiln [1].

As highlighted by Mudgal et al, WPC is an important raw material for cast stone production [3]. The white colour of WPC comes from low iron content (less than 0.5%) [3]. Due to the white colour, it is easier to add different colour dyes to the cement and make cast stone based on the customer's requirement. However, such an advantage comes with high Greenhouse

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gas emissions. Portland cement industry is also one of the major contributors to global warming. The overall cement industry is responsible for 8% of the total global CO_2 emission [4]. Due to that reason, it is necessary to find other eco-friendly and cost-effective replacements to the WPC. The majority of the CO_2 is emitted due to the fossil fuel combustion to heat the cement kiln because the chemical process to make cement occurs at such a high temperature [5]. This paper mainly focuses on finding replacement for WPC that can be used in cast stone.

Fly Ash (FA) is a well-known alternative available for the partial replacement of the WPC. FA is the by-product of burning pulverised coal, due to that reason it is also known as pulverized fuel ash [6]. When FA is combined with lime and water it has the similar characteristic and strength of the WPC [6]. Another study performed by Khankhaje et al found the optimum substitution level of cement with FA between 10% and 30% [7]. The experimental outcome from this study showed that the FA showed higher abrasion resistance and lower drying shrinkage compared when used in concrete. It was concluded from the study that the partial replacement of cement is beneficial for the environment [7]. Since the use of coal is reducing significantly to tackle greenhouse gas emission, the procuring process is getting difficult in the UK as per the government [8, 9]. FA can still be obtained from municipal incinerated waste however the cost of FA makes it commercially unviable for small business.

Another alternative that was available in the literature is called Surkhi which is a brick powder that provided strength to the dams constructed in 1895 before the popularity of Portland cement in India [10]. When Surkhi is mixed with the limestone in a set proportion it acts as a binding agent [11]. Khan et al, have performed studies where the workability of Surkhi has been discussed in a concrete mix as a replacement for Portland cement. The experiment showed that by using 10% of Surkhi as a replacement to Portland Cement a strength of up to 35 N/mm^2 can be achieved. Since it is a brick powder, the colour of Surkhi is red [10, 11]. Also, this binding agent is produced in small quantities in India and high import costs will make it unviable for a small business.

First complete replacement of WPC could be Belite-rich Portland cement (BRC). BRC and WPC have similar clinker mineral composition and both of them are silicate cements and have same grey colour [12]. However, the firing process of BRC and WPC differ. BRC has a higher C_2S content lower C_3S content which is less than 35% as compared to the OPC [13]. Therefore, the BRC produces low heat during the curing process. As per Tongbo Sui et al, BRC can reduce the carbon emissions by 20% compared to the OPC [14]. However, due to lower heat generation, the BRC gains its strength slower than any other Portland cement [14]. Xuan et al have mentioned in their study about Limestone calcined cement (LC3) which is a new composite cement consisting of limestone, clay and cement [13]. This composite cement uses limestone and calcined clay as supplementary materials and increases the economic efficiency whilst also reducing the environmental impact [9]. The mechanical properties of LC3 are similar to those of Portland cement and it is highly durable. Based on the calcined clay the colour of the LC3 varies from grey to different shaded of red. When mixed with limestone it gives a shade of bath colour [15]. In a study performed by the da Silva et al, it was found that the LC3 reduces the carbon emissions of the by 50% compared to Portland cement [16].

Ground granulated blast-furnace slag (GGBS) is added to the cement to reduce the environmental impact as well as improve the strength of the concrete. GGBS is obtained as the result of quenching molten iron and steel slag. GGBS is a latent hydraulic binder forming calcium silicate hydrates after it water is added. As per Sakai et al, it is more efficient than the fly ash. It was also discovered in the study, that GGBS can reduce the carbon emissions between a range of 50% to 90%[17]. GGBS is off-white in colour [18]. Even though GGBS is an ideal partial replacement of the cement it lacks the adequate supply due to constantly shrinking steel and iron industry in the UK [19].

The last alternative is the Magnesium-based cement. In this type of cement, magnesium is combined with carbonate, Phosphate, silicate-hydrate and oxysalt. Even though the Magnesium based cement are 60%-90% greener compared to the PC, the higher cost of production reduces the chances of complete replacement of the PC [20]. Furthermore, due to the low pH value within the cement, it reacts with the steel reinforcement which withholds this type of cement to be used within the large structures.

All the alternatives of the cement have been listed above. However, it is hard to select from many criteria such as cost effectiveness, environmental credentials as well as mechanical properties of the material. To select the best alternative to the WPC a methodology is required. A Multi-Decision Criteria Analysis (MCDA) can be employed to achieve this aim. MCDA methods such as (VIekriterijumsko KOmpromisno Rangiranje) VIKOR have been used in studies to evaluate the cement manufacturing methods [21]. Similarly, two phase MCDA which includes Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) approach to rank different types of high performance concrete mixes based on the workability, strength, and durability [22]. Similarly in metal casting industry, TOPSIS MCDA has been used numerous times for example in selecting the material for the hydro-turbine material [23]. However, none of the studies have ranked different types of cements based on their technical, environmental and financial criteria. In cast stone, the colour of the final product is non-trivial. The ingredients within the mix affect the overall colour. To rank, colour of the cement should also be included in the analysis as it will affect the overall decision about selecting the alternative. None of the studies have included colour in their decision criteria. This study uses automatically weighted high-resolution mapping of multi-criteria decision TOPSIS analysis developed by Pagone et al to find the complete or partial replacement of the WPC for cast stone [24]. This method requires no interference from the decision maker hence providing the result without any external influence [24]. More about this method is explained in the next section.

2 Methodology

As briefly mentioned above, automatically weighted MCDA TOPSIS is used within this study as it integrates with this methodology. By finding a business viable alternative to cement, the overall carbon dioxide emission can be reduced. The methodology used in this paper is covered into three parts as shown in figure 1.

2.1 Choosing alternatives, data collection and data preparation

In this step of the methodology, a literature review is performed where different replacements are identified. The properties of material are divided into technical, environmental and financial criteria. These criteria are further divided into sub-criteria. So, the technical criteria has hydration, strength and colour families as the sub-criteria. Whereas the cost comes under financial criteria. Similarly, carbon dioxide emission is a sub-criterion of environment. All the data on these criteria has been collected during literature review. It is important to arrange the data in a table for the next step.

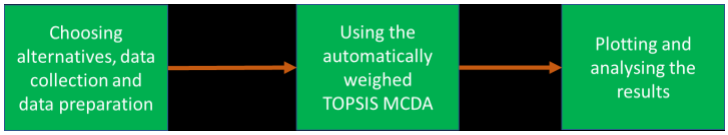

Fig. 1. Methodology

2.2 Using the automatically weighted TOPSIS MCDA

The automatically weighted method is developed by Pagone et al and the working of this method has been explained in detail in the study published by them [24]. This technique cover all the scenarios giving each sub-criteria priority in all four laws i.e., "First two", "Halving", "Quadratic" and "Uniform"[24]. The input data is arranged in the following format below in a '.csv' file. In the uniformly distributed, equal weightage is given to each criterion.

Four sets of analysis are performed and mapped where combinatorial ranking of categories are considered [24]. The four analysis are:

1. Uniform – In this case each criteria is given equal weightage.
2. "Halving": As the name suggests, the weight is halved at next position in the ranking.
3. "Quadratic": A furthermore aggressive reduction in the ranking according to quadratic expression mentioned by Pagone et al [24].
4. "First two": The distribution of the weight is governed by the first two categories.

The importance of each criteria is dictated by the initial letter of the relevant criteria. For example, on the x-axis of "first two" chart, if labeled "fte" where 'f' stands for finance, 't' stands for technical, 'e' stands for environmental. in such case finance has the priority followed by technical and environmental.

Sub-Criteria	Impact	Criteria	Alternative 1,2
Sub-criteria 1	+	Criteria 1	
Sub-criteria 2	-	Criteria 2	
Sub-criteria 3	-	Criteria 3	
Sub-criteria 4	+	Criteria 2	

The impact category does not asks the decision maker for any input other than '+' or '-'sign. So for example, the bigger the value in the row better it is for the sub-criteria 1 and 4 which fall under Criteria 1 and 2. Similarly with the '-'sign, lower the value, better it is for the sub-criteria 2 and 4. However, no weightage is required from the decision makers [24].

2.3 Plotting and analysing the results

As the result of running the Automatically Weighted TOPSIS MCDA, the alternatives are ranked accordingly. The output of this method comes in '.csv' file format and number of output files depend on the number of alternatives as each scenario is covered. These graphs cover all the possible scenarios giving each sub-criteria priority in all four laws i.e., "First two", "Halving", "Quadratic" and "Uniform. The results can be plotted graphically to view easily and better interpretation.

3 Case study

The above-mentioned methodology was applied to a cast stone manufacturing company in the Northamptonshire, United Kingdom. The company produces cast stone in different colours such as Bath, Terracotta, Slate, white and Portland. The products of this company were divided into product families based on their colour. The colours of each alternative have been mentioned in the literature review. They represent the number of options a cast stone can be produced in if an alternative cement is used. For example, a slate colour cast stone can easily be produced using a grey cement alternative i.e. Belite rich Portland cement. However, Belite rich cement cannot produce any other colour other than slate. For this case study WPC has been included to have a better comparison of the current and future state.

3.1 Choosing alternatives, data collection and data preparation

As the first step of the methodology, the alternatives are identified which are mentioned below through a literature review. The three criteria chosen are Financial, Environmental and Technical. The sub-criteria are cost, carbon-emission, cube strength, hydration and colour family. Table 1 shows all the alternatives.

3.2 Using the automatically weighted TOPSIS MCDA

The data has been arranged ready for the Automatically weighted MCDA as shown in the table below. The table below is input as a .csv file.

Table 1. The alternatives of WPC arranged for automatically weighted MCDA

Sub-criteria	Impact	Category	White Portland Cement	Ferrite cement	Belite rich Portland cement	GGBS	Calcined kaolintinic cement	Magnesium based cement
Cost	-	Financial	6	19.14	10.96	3.25	5.23	4.03
Carbon Emission	-	Environmental	652.2	435.4	497.6	155.5	491.38	186.6
Cube strength	+	Technical	20.4	25	54.7	64.2	36.6	83

Hydration	-	Technical	28	7	34	28	7	28
Colour	+	Technical	5	1	1	1	5	1

4 Result

4.1 Uniform distribution

In this category, the weight has been uniformly distributed in all the categories listed in table 1. As shown is the figure 1, GGBS is the winner cement alternative followed by the Magnesium based Cement. Ferrite cement is the least desired alternative. Currently, the company uses WPC, which holds the fourth rank in the unform distribution. A further close analysis of the cement can be seen in the next section where the cement is ranked based on combinatorial ranking.

Combinatorial ranking of categories by importance: Halving, quadratic and first two

As explained in section 2.2, the order of importance for categories is determined by the position of the first letter of the corresponding category in the identifier on the x-axis. Figure 3 (A) shows the “Halving” category where the weightage is halved. In “Halving”, GGBS cement has the highest score in four categories i.e., ‘fet’.’fte’, ‘eft’ and ‘etf’. When technical criterion is given importance, Calcined kaolinitic cement has the highest score. The overall second-best performer in this category is Magnesium based cement. The lowest score was from Ferrite cement for categories ‘fet’,’fte’, eft’ and ‘tfe’. For ‘etf’ was WPC.

In case of “quadratic”, as it shown in figure 3 (B), GGBS has the highest score except in ‘tfe’ and’tef’ where technical category is given importance. In those two categories, Calcined kaolinitic cement has ranked the highest. Ferrite cement ranked lowest when financial criteria is given importance. In terms of environmental criteria, WPC has scored lowest. Belite rich cement scored lowest when technical criterion is given importance.

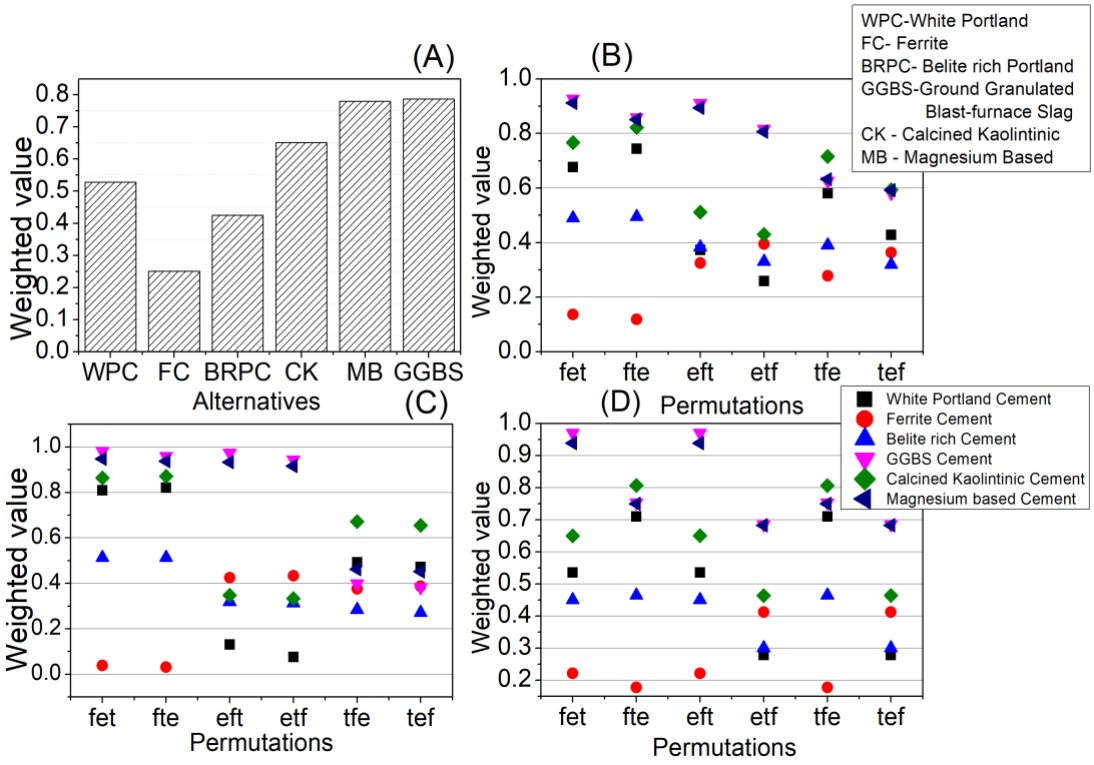

Fig. 2. Ranking of each alternative with weight distribution for "Halving" (A), "Quadratic" (B) and "First two" (C). The first letter of x-axis denotes three criteria i.e., F: Financial, E: Environmental and T: Technical

"First two" shows similar results to "Quadratic" and "Halving". As shown in figure 3 (C) In "First two" GGBS has the highest score except for 'tfe' 'fte' and 'tfe'. Ferrite cement is the lowest performer in 'fet', 'fte', 'eft' and 'tfe' whereas, WPC is lowest performer in 'etf' and 'tef'.

The most occurring alternative from all the cases has resulted in ranking best option has been shown in figure 4. According to the ranking, GGBS is ranked highest followed by Calcined kaolinitic and Magnesium based cement.

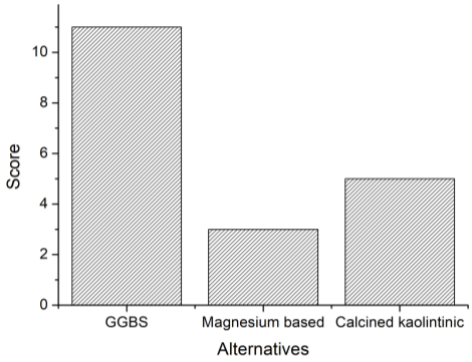

Fig. 3. Overall ranking of alternatives based on occurrence as the best option in each category

5 Conclusion

In this study, five alternatives of White Portland Cement were identified that can be used as binding material in cast stone. The mechanical properties, cost and environmental impact of each alternative were used to select the best available option. To select the alternative, automatically weighting TOPSIS MCDA method was employed. Five alternatives have been found through the literature review and presented in this study. White Portland cement has also been included in the study which is currently being used in cast stone production. Each alternative was divided into three criteria i.e., environmental, financial and technical. As per the results, GGBS cement can be an excellent alternative to the WPC. Being the cheapest cement, it has the lowest carbon emissions of 155.5 kg/tonne. However, it has two limitation first is the colour of the cement and secondly, the availability in the UK market. As cast stone is made in different colours currently, it can only be used in grey colour. Furthermore, as explained in section 1, the availability of GGBS is not suitable for mass production. Similarly, the other two options i.e., Magnesium based and Calcined kaolinitic cement are not available for mass production hence making White Portland cement the most suitable cement to be used in cast stone commercially. However, for a small cast stone manufacturing enterprise, GGBS cement is recommended.

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