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Integration between Sustainability and Value Engineering in the Production of Eco-Friendly Concrete

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Abstract: The global concrete and construction industry's growth has led to a shift in priorities, with a greater emphasis placed on sustainability. Hence, with technological advances, the concrete industry seeks additional cementitious materials to produce value-added products. By emphasizing the financial, ecological, and technological benefits of using fly ash as a partial cement replacement, the study constructed a framework which integrates the economic, environmental, and social pillars of sustainability through value engineering. Experimental results from 42 previous studies are analyzed and presented to underline the unique characteristics of fly ash concrete alternatives across five criteria (replacement, strength gain, compressive strength, slump, and permeability), showing how they differ from conventional concrete, and how they can be used to implement sustainable practices with positive financial outcomes. This study showed that the alternatives' value gradually increases up to two times at 50% cement replacement. On the other hand, while the construction cost gradually increased to a peak of 19.69%, the life cycle cost went down by 41.45% at the same percentage. Thus, customers can emphasize the superiority of eco-friendly concrete while also highlighting the economic benefits, making it a more competitive option for them and expanding its market.

Keywords: fly ash; value analysis; function analysis; sustainability; life cycle cost; AHP approach

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1. Introduction

It is a fact that concrete is one of the most competitive building materials and that it has the potential to last for centuries [1]. It can be blended with fly ash (FA), silica fume, blast furnace slag, meta kaolinite, and limestone powder. Modern concrete typically incorporates air-entraining agents, superplasticizers, retarders, and corrosion-inhibiting compounds. Thus, we are dealing with a complicated, not-fully understood binder system [2]. Significant opportunities for concrete optimization exist, namely, facilitating the use of new processing, mixing, and setting techniques [3]. Determining whether a product is valuable and worth buying for the customer is impossible until the relationship between the cost of the product and its functions is resolved. Value engineering (VE) is a systematic and organized technique for providing the reliable performance of functions to meet customer needs at the lowest overall cost [4]. Products cannot compete in today's market solely based on price. Consumers will not buy a product if it is too expensive in comparison to the value it provides. Therefore, the manufacturer will have to achieve the optimal balance between product value and price. It is important to strike a balance between features and price. This equilibrium is what gives a product its worth. Products are judged by their value to the consumer [5]. In countries that do not have fly ash supplies locally, such as Egypt, producing fly ash cement is more expensive than ordinary cement due to import costs. Despite its superior performance over ordinary cement, the higher price makes fly ash cement an unjustified investment; additionally, the cement industry is known for its low-profit margins. However, if the life cycle cost of cement is included in the equation, then alternative cement can be viewed as economically attractive. Meanwhile, consideration of performance, durability, and long-term environmental effects, as shown by value

comparison, also plays a key role in the market's adoption, establishing higher confidence in the material and making it significantly more desirable.

Many studies have used VE in construction and concluded that it has an impact on project prices, quality, the environment, and global green construction, which considers both the initial and life cycle costs. Rachwan et al. [6] demonstrated how VE and sustainability benefit both the economy and the environment. Their study investigated the use of sustainable VE in a large residential project. Yu et al. [7] investigated how VE influences embodied GHG emissions in the Australian built environment. The case study demonstrated that the dematerialization of traditional VE can improve the environment. Tang et al. [8] showed VE to be a problem-solver in the marine construction business. To collect and evaluate engineer contributions, their VE technique formalized solution value and quantitative performance criteria. Rani [9] discovered the most cost-effective way to enhance the structure without sacrificing its value or function, showing that VE maximizes project cost savings while maintaining high development quality. Fang et al. [10] used VE theory to assess the incremental cost and benefit of prefabricated and cast-in-place buildings to compare the project's output value over time. The estimates showed that all aspects of prefabricated buildings are improving. Glass et al. [11] emphasized innovation in reinforced concrete building technologies in the United Kingdom. Concrete Technology Innovation Evaluation Using the VE project assessed innovation uptake in reinforced concrete structures using VE. Katzenbach et al. [12] demonstrated that the design of geotechnical structures prioritizes safety, efficiency, and sustainability; by establishing a safe, optimal, and sustainable design, VE saves time, money, and materials. Elhegazy [13] discussed VE in structural engineering, including its numerous dimensions, recent activity in key areas, and future research and implementations. According to Mehta et al. [14], VE has a variety of applications. Quality and affordability are combined in VE. El-Alfy [15] followed the phases of the VE work plan and the sustainable building recommendations to explore sustainable building design and materials. Mahdi et al. [16] employed VE to assess Slip Forming technology in modern building projects, finding that VE increases function, time, performance, and cost by minimizing energy use. Russell et al. [17] investigated constructability and how programs, such as the master builder, combine design and construction. Total quality management and VE both claim that constructability is important.

Other researchers have utilized VE to examine concrete, and all have concluded that VE on concrete mixtures improved building quality, lifetime, resource optimization, waste reduction in concrete mixtures, and sustainability. El-Baghdady et al. [18] proved that value-designed concrete mixtures improve the quality and productivity of ready-mixed concrete in construction and hydraulic projects. Huang et al. [19] examined five concrete building project alternatives using VE and found the optimum solution is self-compacting concrete, which uses industrial byproducts, making it less expensive and more environmentally friendly. VE is used by Komarudin et al. [20] to produce cheaper, high-quality concrete from the best fly ash. Shaikh et al. [21] evaluated normal concrete and lightweight concrete for fresh, hardened, and durability characteristics such as density, workability, compressive and flexural strength, modulus of elasticity, rapid chloride ion penetration, and water absorption. According to Sudiarsa et al. [22], the outstanding design of the building ensures cost-effective development. The VE research allowed the best alternative to be selected in the creative stage by modifying concrete quality and composite.

Despite the significant research efforts that have been and will continue to be made, most articles on concrete have been written by scientists or industry experts with extensive knowledge, rather than by concrete consumers. Furthermore, concrete suffers from a lack of communication, including a lack of demonstrating its power. Too often, concrete is described in terms of its 28-day compressive strength, without regard to the environmental circumstances in which it will have to perform its structural role. In addition, concrete is a complicated material that not only follows the laws of physics, chemistry, and thermodynamics, but also follows the laws of the market [2]. Our aim, then, is to offer user-oriented research.

In fact, eco-friendly concrete can be produced, but will it be sold, and will there be a market demand for it? This is an open question. The answer is environmental and economic since it will be determined not only by the initial cost but also by the life cycle cost and value analysis. Therefore, integrating VE and sustainability is essential to guarantee the product's commercial and environmental success. For this reason, this study presents a constructed framework across the three primary axes of sustainability (economic, environmental, and social) and follows the VE technique supplied by SAVE International.

From 1987 to 1997, several researchers coined words such as green manufacturing, sustainable manufacturing, clean manufacturing, and so on. Over the years, more than 100 definitions of sustainability have appeared. These definitions may differ in detail [23], but they all agree that sustainability is defined as the intersection of the economy, social development, and environmental objectives. Sustainable development can be defined as the optimal balance of the development of these three sectors [24].

To what extent should eco-friendly materials be utilized in the concrete industry? This is another open question. The relationship between utilization rate and value is not always positive. To guarantee the product's success, it is important to analyze how different usage rates will affect the product's total value to the customer. VE is used as an optimization tool in this study to examine nontraditional solutions for a variety of concrete purposes. Several experimental results from previous studies are analyzed and presented.

It is essential to examine the problem's assumptions and data to find a workable solution. There are always assumptions; tests and experience-based research have often been used to challenge assumptions. Often data that are used as facts are in some part, small or large, assumptions. Using perceptive inquiry and deep analysis, they distinguish assumptions from facts, determine whether further information or data can be acquired to turn certain assumptions into facts, and adjust some remaining assumptions to be more accurate [25].

1.1. Environmental Impact of Concrete

Sustainability concerns are of the utmost importance for the concrete industry and scientific community. Sustainability is a development that meets the needs of the present without compromising future generations' ability to meet their own needs [24]. It has a widespread impact on preserving natural resources for future generations and on attempting to provide suitable alternatives to these resources [26,27]. Therefore, in 2015, 90 countries included actions to reduce building-related emissions or improve energy efficiency in Paris, which was a landmark in global climate change efforts that aim to expand adaptive capacity, build resilience, and promote sustainable development [28]. Even though concrete has the lowest embodied energy and carbon per unit volume of any building material [24], because of its huge production quantities, it has a significantly greater effect than anticipated [1].

Climate change is among the most urgent problems facing the world today. The atmospheric concentration of carbon dioxide, a key driver of the greenhouse effect, is at an all-time high [29]. About 6–7% of the world's total CO_2 emissions come from concrete production, and 80% of those emissions come from Portland cement, the main binder of concrete [30,31] The calcination reaction that occurs during cement production produces about 0.55 tons of CO_2 for every ton of cement produced. In addition, it necessitates the combustion of fossil fuels, which results in the emission of an additional 0.40 t of greenhouse gases [31–33]. Moreover, the vast majority of the raw materials used to make concrete are derived from nonrenewable resources, making the process itself unsustainable [1,29]. To burn clinker, about 1.7 tons of raw materials, frequently limestone, are needed for every ton of clinker made: 6.97 billion tons per year [27]. This process has major consequences for the environment, which increases awareness and focus on a variety of sustainability issues. It has also increased the promotion of scientific research and directing more cement industry researchers and professionals to investigate unexplored sustainability paths, identifying new alternatives, options, and solutions, as well as economic benefits [1,26,27,31].

1.2. Fly Ash Concrete as a Solution

Fly ash refers to fine particles collected in coal power plants' dedusting systems. The coal's emitted minerals liquefy, evaporate, consolidate, or agglomerate during/after burning. Rapid post-combustion cooling creates sphere-shaped, amorphous FA grains due to surface tension [2,34–36]. Fly ash (FA) is considered an important supplementary cementitious material in the world [24,29,34,35,37]. The more fly ash is used in concrete, the less FA goes to landfills, and less cement production means fewer CO_2 emissions. FA is collected in coal power plants' dedusting systems, though coal is and will remain the world's most important energy source for increasing electricity production. Every week, a new coal-powered plant opens [24]. In addition, about eight hundred million tons of FA are produced annually around the world, and this number is expected to rise to 2100 million tons in 2031–2032. FA usage is 39% in the US and 47% in Europe, while the global average is 25% at 200 million tons per year [27,38]. Therefore, there is still a significant chance of further raising fly ash content in concrete, since much of the fly ash is still being diverted to landfills, and current landfills are full of fly ash that might potentially be used in concrete [35,39,40].

2. Methodology

The study tried to bridge the present knowledge between concrete, sustainability, and VE, which has recently been shown to positively affect not only product costs and quality but also environmental outcomes and the worldwide trend toward green building [6]. Value is what makes us choose product A over product B. Any product is regarded as having excellent value if its performance and price are satisfactory [4]. In contrast, according to the reverse definition, a product is deemed to be of poor value if it lacks either adequate performance or cost. The study is a byproduct of beneficial solutions generated by alternatives. The research tried to link how the alternative works, how much it costs, and how much it helps. In other words, consumers do not just pay for a product; they also pay for the features that come with it.

The study methodology was based on the application of value engineering as a technique for assessing eco-friendly concrete and establishing its viability as an alternative to conventional concrete. Fly ash concrete was employed as a representative of eco-friendly concrete. Altering the percentage of cement replacement was used to generate alternatives (0–50%). The influence of the replacement percentage on the properties of concrete and consequently its cost and value were determined. Five comparison criteria were selected and the results of the replacement rate were compiled for these criteria from 42 previous studies, so that the results would be more comprehensive and representative. The relationship between the replacement rate and each comparison criteria was drawn separately, and then the trend line was deduced and the relationship between each pair of variables was concluded. A questionnaire was issued to the Engineering consulting offices to assess the relative weights of the comparative criteria, as the consulting offices are responsible for defining requirements and subsequently selecting eco-friendly concrete. The usage of the Super Decision software was determined to make a decision in a multicriteria environment and to assess the performance and importance of alternatives based on their qualities, while taking the customer's requirements into account. Next came the task of cost calculation, in which not only the initial cost, but also the life cycle cost, was estimated using Life 365 software so that the results were more comprehensive and representative, facilitating the decision-making process. This was the most important step in the study, as it was where the value of the different alternatives was measured based on the initial cost and the cost of the life cycle, where the decision could be made, and where the extent of the superiority of eco-friendly concrete over conventional concrete could be assessed to achieve the study's goal.

By following the six-step "VE job plan" from the SAVE methodology [41], as shown in Figure 1, the optimal balance between function, performance, quality, and cost can be achieved through the use of VE as a problem-solving technique, producing an optimal and

non-traditional solution. VE is a technique that uses an approach not dissimilar from that of scientific study. In light of this, the following research procedures have been integrated: the introduction and problem statement are matched with the VE information segment, and during this the problem and its present viable solutions are outlined. Next, the available alternatives are analyzed. The VE study is initiated using function analysis (using the FAST diagram), then moves to the VE creativity phase (during which it explains the performance of the alternatives relative to the comparison criteria), the VE evaluation phase (during which it defines the performance values of the alternatives and their cost), and the VE judgment phase, which matches the results and discussion stage (during which the value analysis is carried out). Finally, it reaches the presentation phase, which matches the conclusion stage, which deals with the results of the research and its recommendations.

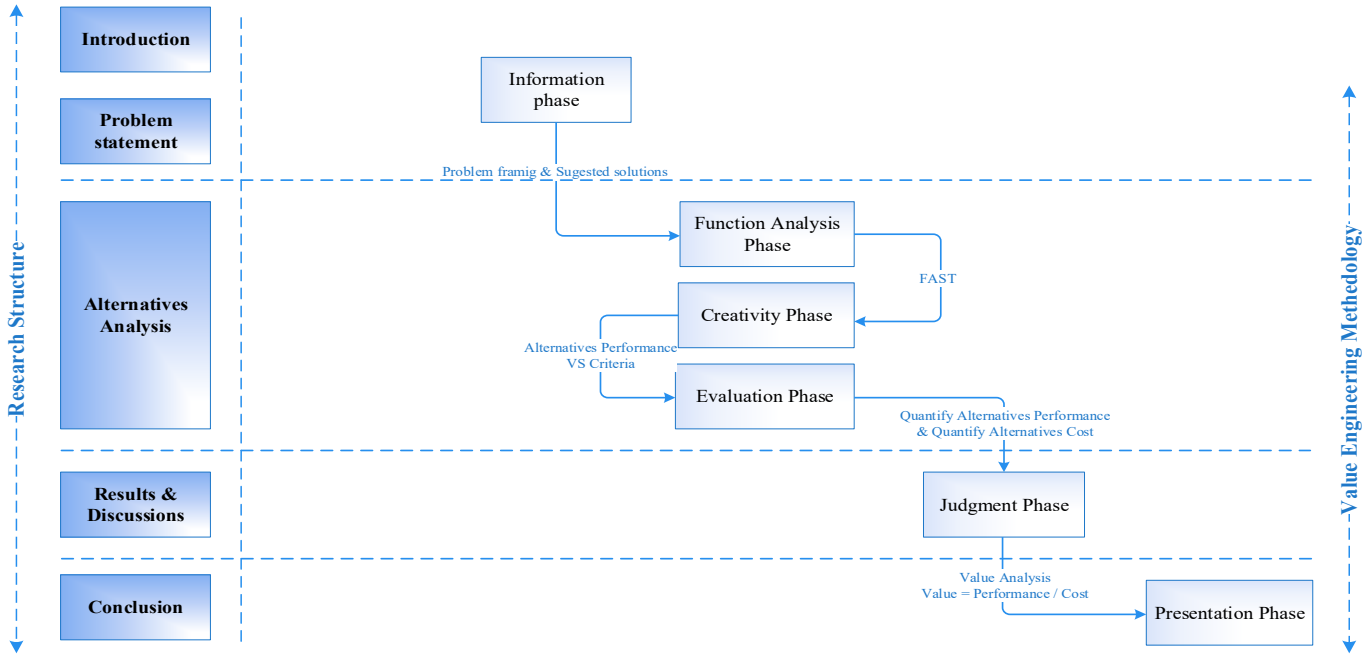


Figure 1. Research structure according to Value Engineering methodology.

3. Alternatives Analysis

Fly ash was adopted as a solution to the issue. We analyze the alternatives, which are the percentages of replacing cement with FA, ranging from 5% to 50%, to validate the hypothesis and achieve the optimum value compared to conventional concrete.

3.1. Function Analysis Phase

Function analysis is the key component of value analysis, because one of the most difficult challenges in problem solving is defining the problem in a way that leads to significant improvement [4]. As the proverb says, "a problem that is clearly defined is half solved" [25]. For example, the doctor spends most of his or her time attempting to interpret the patient's symptoms. Once the issue has been identified, treatment becomes routine. It can be achieved by separating the problem from its apparent symptoms and analyzing its functions. The term "function" refers to the result that a product or service must produce for the customer. A requirement, goal, or objective is not an action; the function is the reason for taking that action. It is difficult to determine which functions and features customers want to purchase. What features, components, or steps in a product would give customers more value? How can functionality be improved while costs are reduced? In that spirit, with the help of the FAST Model technique, as shown in Figure 2, value analysis can be used to address such concerns and develop a good strategy for success in a competitive market [5]. It can moreover be used to attempt to comprehend how a system should and

does function, in order to comprehend the need to detect problems, determine causes, and propose solutions [4].

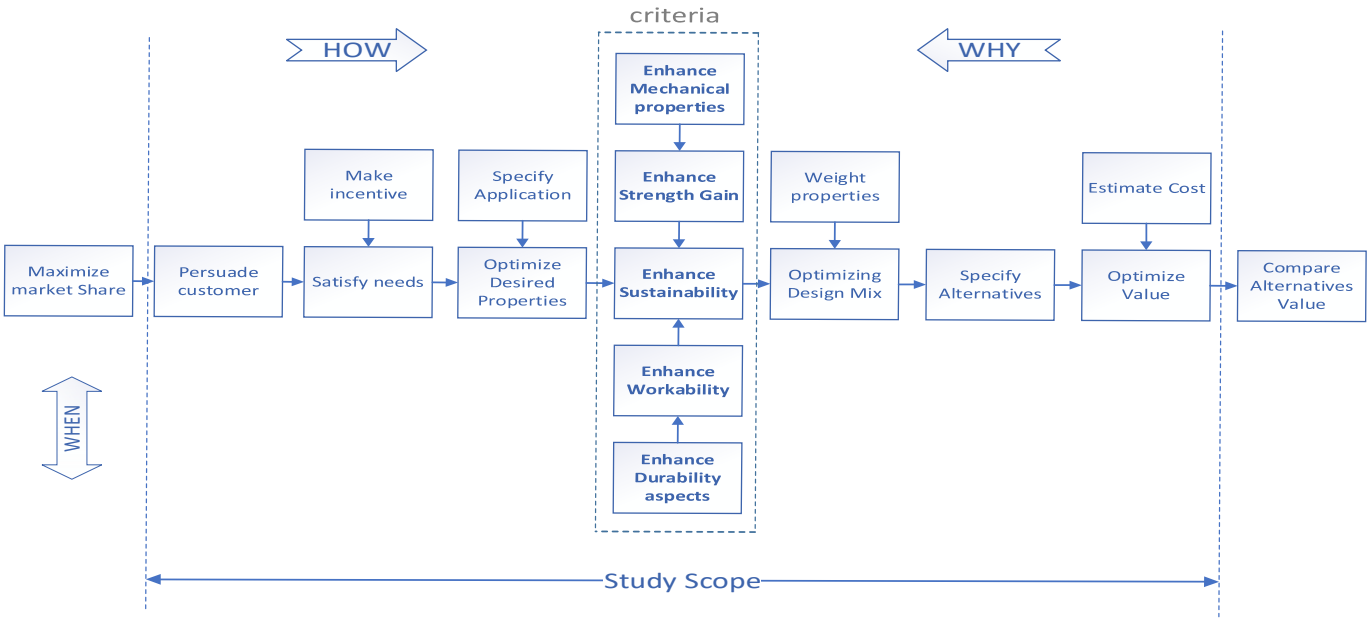


Figure 2. Eco-friendly concrete function analysis structure diagram (FAST).

At the heart of the FAST-modeling process rest two powerful questions that, if asked strategically in researching for information, open the door to a wealth of knowledge waiting to be freed, hidden under assumptions and misinformation. Those two questions are: how, and why? [4]. Ask "how" questions from right to left as follows: how to maximize market share (by persuading customers)? How to persuade customers (by satisfying their needs)? Then, beginning on the left, ask "why" questions, such as: why compare alternative values (to optimize value)? Why optimize value (to specify alternatives)? Next, going up and down, make "when" statements, such as: when you satisfy needs, (you may need to make incentives). It is not appropriate to assess the FAST model as correct or wrong as it is nondimensional, but it is necessary to confirm its validity and determine whether it accurately represents product challenges or not, following the logic in Figure 2 and answering the questions of the previous step.

The FAST model is then case-specific and used as a visual aid in describing the product functionally to the customer and the performance metrics of the valued functions. As the customer is the foundation of success, the research depends on the most important five criteria chosen by an initial problem-framing market survey among the variety of product criteria. These criteria are mechanical properties, strength gain, sustainability, workability, and durability. The FAST model was then used to compare the functional performance of competitive products, which highlights the strengths (ours) and weaknesses (theirs) of the products being compared [4].

3.2. Creativity Phase

Einstein said that when there is a problem to be solved, "Creativity is more important than knowledge ". Having acquired understanding and information, the foundation for the application of various techniques has been laid to generate every possible solution [25]. The study tried to decide which is the best alternative among ten by comparing their performance against the previously selected five criteria. As a consequence, multi-criteria decision-making (MCDM) was conducted. Therefore, the Analytical Hierarchy Process (AHP) was employed, as shown in Figure 3, which is used to solve (MCDM) problems, which are choice problems where alternatives are evaluated concerning multiple criteria [42], to make thinking explicit and generate a list of feasible alternatives (0–50% fly ash

concrete mixes) before committing to an action. It is about using intelligence to produce options by understanding how solutions work since their value comes from the way they enable functions to be performed [4].

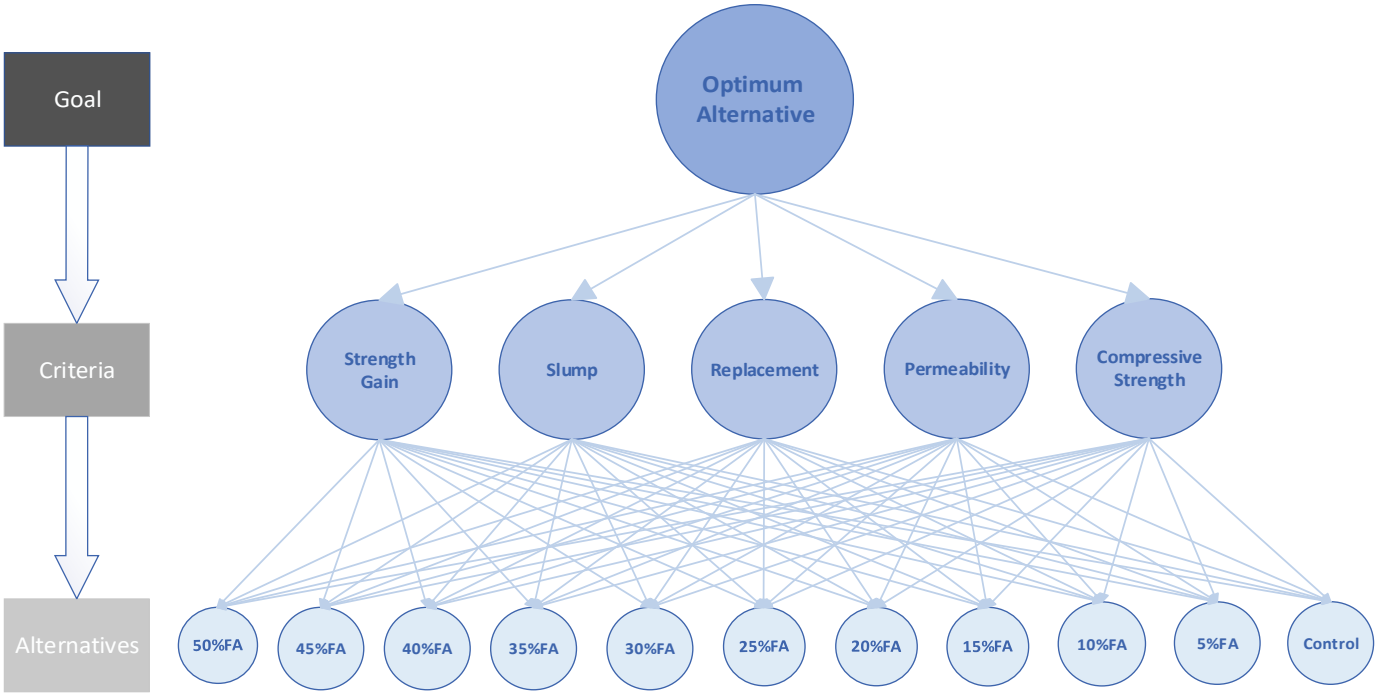


Figure 3. The AHP diagram for fly ash concrete alternatives.

Figure 3 shows the Analytical Hierarchy Process network (AHP). The alternatives start at 0% FA and go up to 50% FA as they move through the five evaluation criteria to find the best solution. The best solution is found by comparing the performance of each alternative on the scale of the criteria and the customer's preferences.

When determining customer value, it is important to consider the particular circumstances surrounding the functions being evaluated rather than make broad assumptions about customer value preferences [5]. In addition, metrics show customers how well solutions fulfill underlying functions [4]. Specialists have found conflicting results regarding the mechanical and durability properties of concrete due to FA's chemical and physical properties. Furthermore, not all coals contain the same impurities, as the fly ashes recovered in the dedusting system vary in chemical and physical composition based on their source and geology, so specialists have found a high degree of dispersion in the results [2,27,35,43–45]. As a result, the results of one study cannot be relied on to obtain reliable data, so data from 42 separate studies were compiled in Table 1, showing the reference and replacement percentages for each study separately, as well as the investigated corresponding criteria to determine the overall pattern of the influence that fly ash has on the properties of concrete. The analyzed studies are summarized in Table 1, which includes details about their references, replacement rates, and investigated criteria for each study separately.

Table 1. The investigated properties versus the percentage of replacement (an "X" means that the related research investigated the corresponding criteria).

FA Replacement (%)	W/B	Slump	Strength Gain (7/28 Days)	Comp. Strength (90 Days)	Durability (90 Days)	Ref.	Year
0-10-20-30	0.27–0.60	X	X	X	-	[46]	2003
0-10-20-30	0.35–0.70	X	X	X	-	[47]	2004
0-15-25-45-55	0.30–0.50	-	X	X	-	[48]	1998
0-13-20-25-30-33-37	0.50–0.94	X	-	-	-	[49]	2005
0-35-42-50	0.47–0.77	-	X	-	-	[50]	1988
0-20-40-60-80	0.24–0.72	X	X	X	-	[51]	2013
0-20-40-60-80-100	0.35–0.40	-	X	X	-	[52]	2010
0-15-45-55	0.19–0.50	-	X	X	-	[53]	2015
0-5-10-15-20-2-30-35-40	0.40	-	-	X	X	[54]	2022
0-30-40	0.29–0.41	X	X	X	-	[55]	2011
0-10-15	0.25–0.38	X	-	X	-	[56]	1998
0-10-20-30-40	0.35	-	X	X	-	[57]	2018
05-10-15-20-25	0.30–0.42	-	-	X	-	[58]	2011
0-15-30-45-60-75	0.50–0.60	X	X	-	-	[59]	2011
0-40-60-80	0.42–0.89	-	X	X	-	[38]	2015
0-20-30-40-50-60	0.40–0.55	X	X	X	-	[33]	2019
0-25-45	0.19–0.24	-	X	X	X	[60]	2000
0-25-40	0.38–0.75	X	X	X	-	[61]	2012
0-30	0.21–0.54	X	X	X	-	[62]	2005
0-50	0.38–0.60	X	-	X	X	[63]	2005
0-15-30-45	0.35	X	-	-	-	[64]	2022
0-50-70	0.28–0.34	-	X	X	-	[65]	2003
0-20-30-40-50-60	0.30–0.40	-	X	X	-	[66]	2007
0-15-30-50	0.50	-	-	-	X	[67]	2017
0-10-20-25-30-40	0.36	-	X	-	-	[68]	2018
0-10-15-25-35	0.30–0.45	-	-	X	X	[69]	2021
0-10-20-30	0.45	X	X	X	X	[70]	2018
0-10-20	0.28–0.43	X	-	-	-	[71]	2002
0-10-15-20-25-30	0.40	X	-	-	-	[72]	2019
0-20-30	0.35–0.65	-	-	-	X	[73]	2018
0-10-20-30	0.50	X	-	-	X	[74]	2017
0-35-55	0.35	X	-	-	-	[75]	2008
0-40-60	0.40	X	X	X	X	[76]	2015
0-30-40-50	0.40	X	-	X	X	[77]	2012
0-40-60	0.40	X	X	X	X	[78]	2015
0-20-30-40	0.31–0.34	-	-	-	-	[79]	2013
0-10-20-30-40-50-60-70	0.43–0.50	-	X	X	X	[80]	2013
0-30-40-50	0.34–0.50	-	X	-	X	[81]	2006
0-10-20-30	0.32–0.50	-	X	X	X	[82]	2010
0-18-36	0.44	-	X	X	X	[83]	2015
0-30-40-50-60	0.36	-	-	-	X	[84]	2015
0-10-20	0.40	-	X	X	X	[85]	2014

Since the measuring units for the five criteria in the comparison differ, the percentage of change from traditional concrete was used to make the comparison more realistic and practical. Furthermore, each study has unique circumstances that differ from the others, making absolute comparisons impractical. Furthermore, the AHP is a theory and methodology for relative measurement that is not particularly interested in the precise scores of the alternatives but in their relative measurements to determine which alternative is the best. The ultimate goal of the AHP is to provide a rating of alternatives utilizing pairwise comparisons of alternatives as inputs, according to the principle of relative measurement [42]. Therefore, it makes sense to figure out the percentage of change caused by

replacing cement with FA versus traditional concrete for each study separately; this is the heart of the problem.

3.2.1. Strength Gain

The rate of hydration reactions in FA-containing concrete is the first thing to note. When FA Class F is used as SCM, the strength development is much slower than with ordinary Portland cement due to the slow pozzolanic reaction. A concrete mixture with FA causes economic losses in the fast-paced construction industry. This can mean more time and money are needed to remove the forms [86]. However, architects and builders should know that partially negative aspects have advantages in the form of hydration heat reduction or reduction of volumetric changes, increasing strength, and decreasing permeability [2,87,88].

Until about three weeks after placement, the initial strengths of FA-containing concrete are typically lower than those of cement-only concrete [88] By reason of the scope of this study, the changes in the ratio between 7/28 day compressive strengths were calculated to get an indication of concrete strength gain over time.

Figure 4 depicts the impact of the FA replacement rate on strength gain as a percentage of the performance of ordinary concrete. 90% of the results confirm that the replacement has a negative effect, and the trend line indicates that the greater the replacement rate, the more negatively it affects the strength gain. This is one of the drawbacks of its use, so it was considered, but it is also noted that some outcomes are positive, which means that by selecting materials with superior properties, it can either obtain positive outcomes or at least reduce negative results, which will reflect positively on the resultant concrete value. The trend line is represented by the equation $y = -0.0818x^2 - 0.2087x - 0.0286$, where y is the percentage effect on strength gain and x is the percentage of FA replacement.

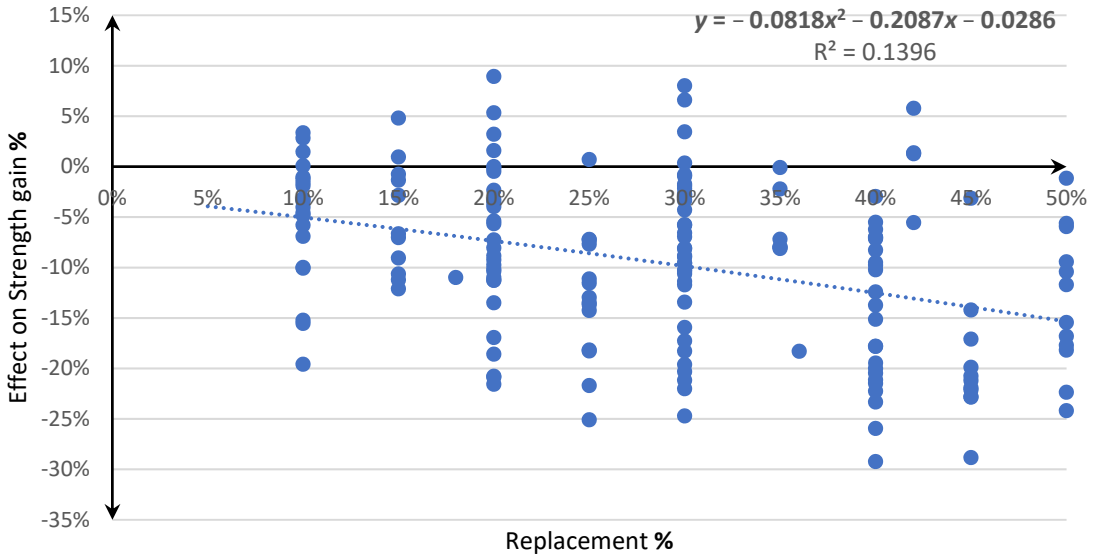


Figure 4. Effects of fly ash replacement on Strength Gain.

3.2.2. Durability

FA is used to improve concrete durability through a pozzolanic reaction during long-term hydration. Fly ash mineral admixtures react with early-age hydration products to form a secondary CSH gel. This gel has less density and volume than C-S-H gel. The gel fills all the pores in the concrete, so it resists environmental deterioration [29,35,89,90]. It also improves concrete durability through thermal gradient control, depletion of cement alkalis, chloride and sulfate resistance, long-term hydration, and reduced reinforcing corrosion [38,89–93]. Increased concrete durability is the key to sustainability because extending the lifespan of a concrete building will relieve some of the strain on the planet's

limited supplies. Copious amounts of energy, materials, and money are wasted when structures deteriorate or fail prematurely [24,94,95]. Optimizing concrete mixture design and reinforcements are also important factors [24]. The denser the concrete is and the fewer voids it has, the longer it will last because it will prevent harmful liquids and gases from penetrating the concrete. Permeability is the key driver for durability, and accordingly, for the purpose of this research, the rapid chloride permeability test has been used as an indication of durability.

Figure 5 shows the percentage difference in permeability between FA concrete alternatives and ordinary concrete performance. It is worth highlighting that all of the results are positive and that the relationship is also positive, emphasizing that the bigger the replacement percentage, the greater the benefits. The percentage of improvement increases until it reaches 30%, then the increase rate decreases, and the optimum result is at 45%. This is one of the best properties that fly ash improves, and it is the main motivator for the use of fly ash, because it not only positively affects the properties of concrete but also prolongs its life, which has a significant impact on the financial and environmental factors. The qualities of the resultant concrete can be increased by selecting materials with valuable properties, which will reflect positively on its value. It is not a secret that durability is not a key requirement of the market these days, and this is a common misunderstanding that we hope to rectify through this research. The trend line can be represented by the equation $y = -3.177x^2 + 2.7402x + 0.0548$, where y is the percentage of the effect on strength gain and x is the percentage of the replacement with FA.

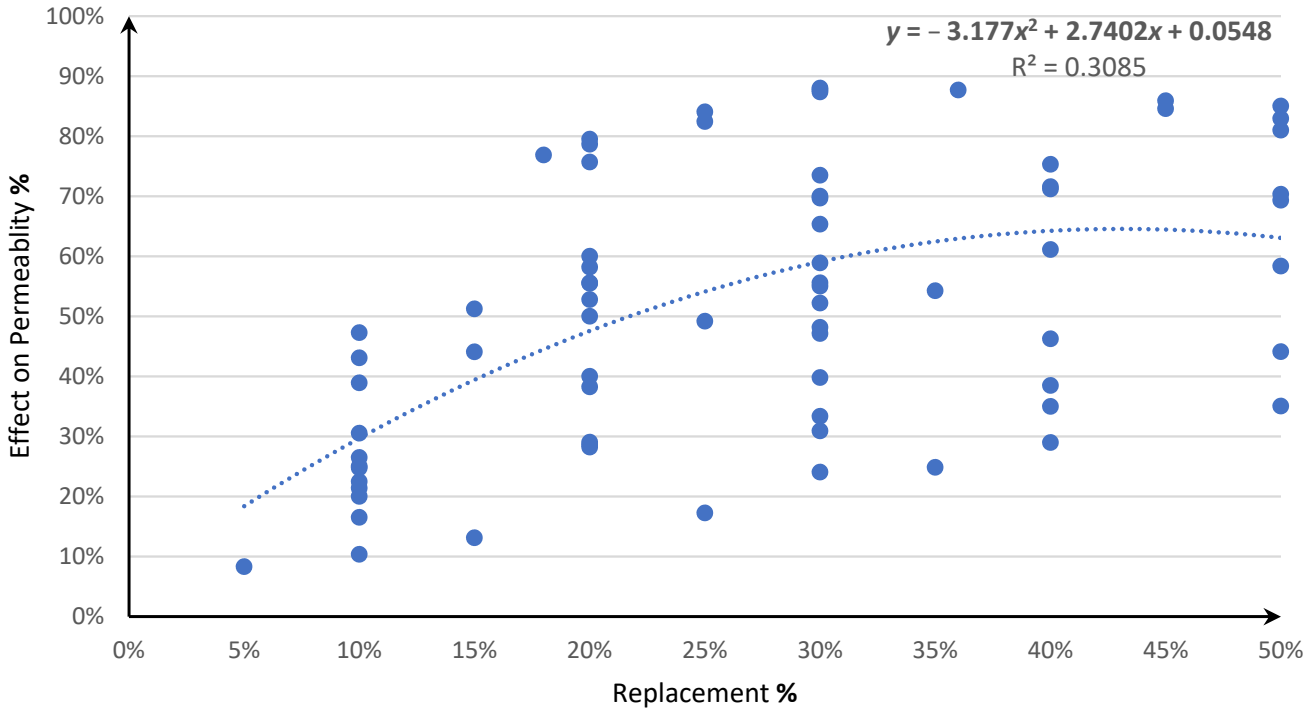


Figure 5. Effects of fly ash replacement on permeability.

3.2.3. Compressive Strength

Increasing the mechanical properties of concrete makes it more environmentally friendly because it requires fewer concrete sections for the same loads, which results in less material consumption and a reduction in carbon dioxide emissions [45]. Fly ash improves the mechanical properties of concrete on the same principle as it improves durability because it chemically reacts after hydration, filling interstitial pores with extra high-strength materials such as calcium silicate hydrates (CSH), improving concrete's microstructure [26,91]. Fly ash concrete has lower early strengths than Portland cement concrete, but at later stages (56 days [24] and 90 days), FA increases concrete's strength

and durability significantly compared to conventional concrete, and the product is more eco-friendly and cheaper than cement [29,35,86,90,95,96].

Although replacing the cement with fly ash improved the compressive strength in some cases, this was not always the case, as shown in Figure 6. The results have a positive effect until a replacement rate of 33% is reached, after which the situation reverses and the effect becomes negative, as shown by the trend line. These results can be interpreted using the equation $y = -1.1216x^2 + 0.2464x + 0.0454$, where y is the percentage of change in compressive strength and x is the percentage of replacement of cement. Close attention must be paid to the outcomes of this particular attribute. Most concrete is sold based on its compressive strength and slump. Furthermore, by utilizing materials with high specifications, the benefit of that attribute can be maximized; it can also be seen that there are outstanding results even when the replacement rate exceeds 33%, which increases the product's value.

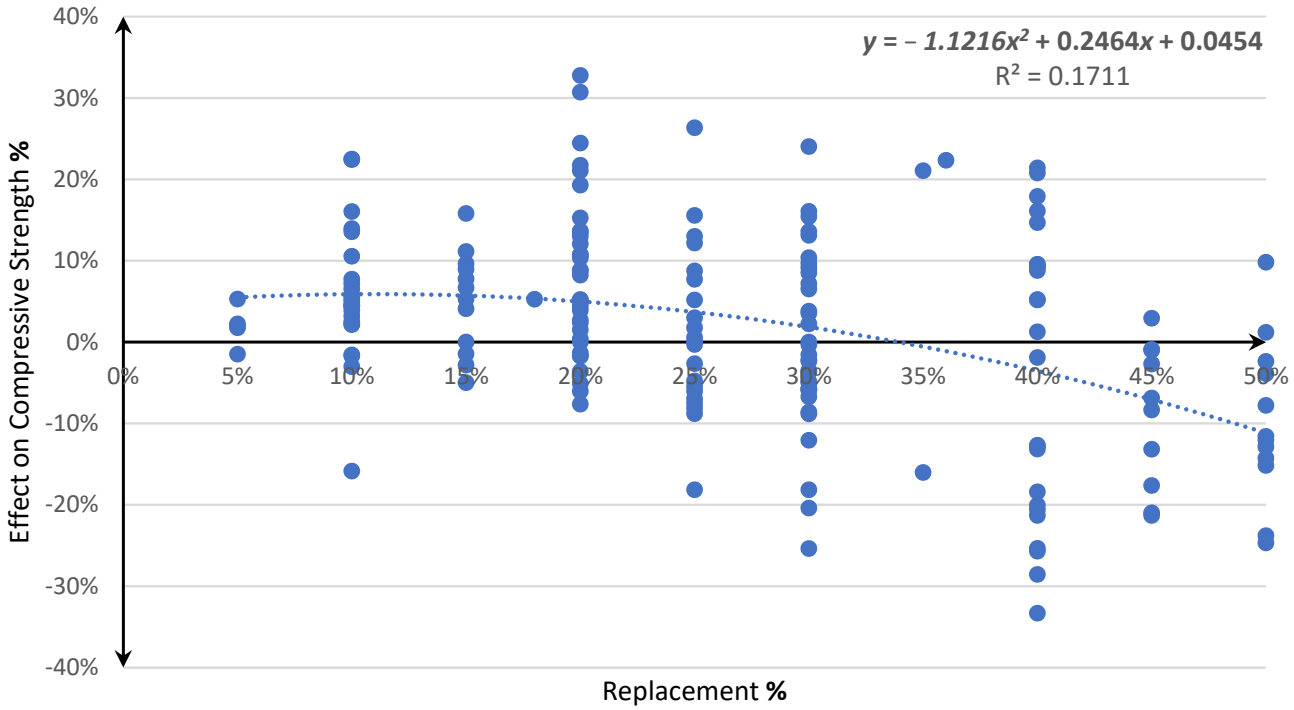


Figure 6. Effects of fly ash replacement on compressive strength.

3.2.4. Workability

FA particles are spherical, so they mix easily. This makes fly ash a desirable concrete admixture [89]. It enhances the workability of concrete by lowering water demand for similar workability, reducing bleeding and segregation, lowering heat evolution, improving surface finish, and decreasing drying shrinkage [29,35,36,38,90–92,95].

Figure 7 shows the impact of the percentage of cement replacement with fly ash on slump compared to the performance of ordinary concrete; the results were positive, but at a declining rate of up to 17% and nearly zero at 30%, before increasing to their maximum levels at 50% replacement, as demonstrated by the trend line and expressed by the equation $y = 1.289x^2 - 0.6013x + 0.0661$, where y is the percentage of change in workability and x is the percentage of replacement of cement. The selection of material will determine the results of the decrease or increase in the corresponding value.

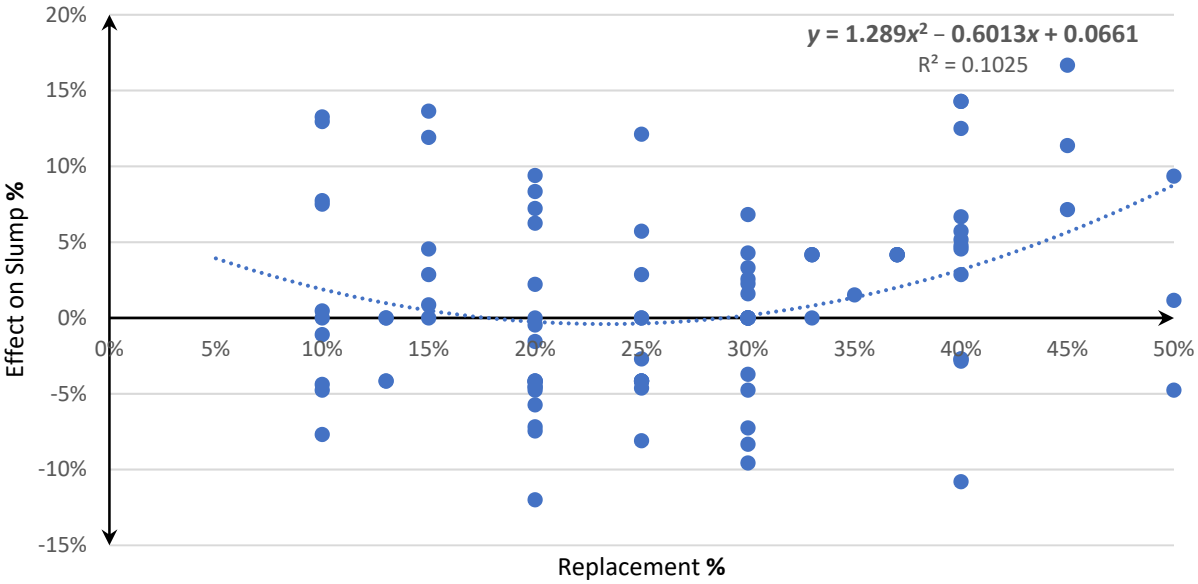


Figure 7. Effects of fly ash replacement on the slump.

3.2.5. Results Overview

To make the data more realistic and representative of the effect, the results of forty-three separate studies were analyzed. By making equations that show the overall average trend, as shown in Table 2, this information was used to find a link between the percentage of replacements and the percentage of change for each of the five criteria that were analyzed.

Table 2. Percentage of change in the investigated properties versus percentage of replacement.

MIX	Strength (%)		Permeability (%)		Repl. (%)		Slump (%)		St. Gain (%)	
	$y = -1.1216x^2 + 0.2464x + 0.0454$		$y = -3.177x^2 + 2.7402x + 0.0548$		$y = x$		$y = 1.289x^2 - 0.6013x + 0.0661$		$y = -0.0818x^2 - 0.2087x - 0.0286$	
	Change	Total	Change	Total	Change	Total	Change	Total	Change	Total
Control	0.00	100.00	0.00	100.00	0.00	0.00	0.00	100.00	0.00	100.00
5% FA	5.49	105.49	18.39	118.39	5.00	5.00	3.93	103.93	−3.92	96.08
10% FA	5.88	105.88	29.71	129.71	10.00	10.00	1.89	101.89	−5.03	94.97
15% FA	5.71	105.71	39.43	139.43	15.00	15.00	0.49	100.49	−6.17	93.83
20% FA	4.98	104.98	47.58	147.58	20.00	20.00	−0.26	99.74	−7.36	92.64
25% FA	3.69	103.69	54.13	154.13	25.00	25.00	−0.37	99.63	−8.59	91.41
30% FA	1.84	101.84	59.09	159.09	30.00	30.00	0.17	100.17	−9.86	90.14
35% FA	−0.58	99.42	62.47	162.47	35.00	35.00	1.35	101.35	−11.17	88.83
40% FA	−3.55	96.45	64.26	164.26	40.00	40.00	3.18	103.18	−12.52	87.48
45% FA	−7.08	92.92	64.45	164.45	45.00	45.00	5.65	105.65	−13.91	86.09
50% FA	−11.18	88.82	63.07	163.07	50.00	50.00	8.77	108.77	−15.34	84.66

Table 2 shows the values of the change resulting from each replacement percentage for the five criteria under study, explaining the equation of the relationship deduced from the trend line for each criterion separately, as well as the percentage of all the results, given that the result of the control (0% FA) is 100% and the value of the change is added to 100%, to be used later as inputs for AHP calculations. The results cannot be generalized as a general effect of replacement with FA, but the results of the real sample that will be used should be investigated to obtain accurate and representative results.

According to the existing results, the criteria do not have the same behavior. The outcomes of some criteria are positive, while those of others are negative. This is obvious in the permeability criteria, which provide the highest performance results by a margin of 64%, while strength gain criteria provide the worst performance results by a margin of −15%;

however, neither of these findings indicate success or failure since customer preferences must be taken into account, which greatly magnifies the impact of one of the factors and causes the increase or decrease to affect the final value, and also because the alternative must be analyzed based on cost as the alternative can have a very high performance but a very high price, so will fail in the market.

3.3. Evaluation Phase

The value equation Value = Performance/Cost is the way that Miles expressed the relationship between function and cost. Miles stated that "all cost is for function" [4]. Customer value cannot be determined unless the relationship between the product's cost and functions is resolved.

3.3.1. Quantify Alternatives' Performance

As mentioned before, every product does not have the same features and quality, so it is necessary to attribute them and rank them against each other, as shown in Table 3, by dimensioning the FAST model. This improves understanding and makes it a more innovative and better problem-solving and planning tool [25]. With the help of the sensitivity matrix, as shown in Figure 8, a combination of attributes that reflect overall performance can be represented, trade-offs between attributes can be weighted, and it can be determined which attribute requires more attention relative to its importance to the customer [4]. A market survey was conducted in Egypt and distributed to the engineering consulting offices, as they are responsible for selecting project specifications. The overall study population consisted of 312 offices and engineering expertise houses specializing in concrete construction, which were registered with the Egyptian Syndicate of Engineers for the years 2021–2022. The total number of responses to the questionnaire was ninety-three, and the questionnaire consisted of a comparison between criteria A and B on a scale of choice ranging from **1** to **9**. As a percentage of the total number of responses, the following were the results:

Table 3. Questionnaire results of the investigated criteria's pair comparisons.

Criteria	Selection (%)									Criteria
(*A*)	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(*B*)**
Comp. Strength	14.0	21.5	19.4	5.4	22.6	5.4	4.3	4.3	3.2	Permeability
Slump	3.2	4.3	4.3	6.5	16.1	15.1	21.5	16.1	12.9	Permeability
Replacement	2.2	4.3	4.3	7.5	20.4	15.1	23.7	8.6	14.0	Permeability
Strength gain	2.2	6.5	5.4	6.5	12.9	12.9	24.7	10.8	18.3	Permeability
Slump	0.0	2.2	3.2	4.3	19.4	4.3	21.5	16.1	29.0	Comp. strength
Replacement	0.0	2.2	5.4	4.3	14.0	10.8	12.9	21.5	29.0	Comp. strength
Strength gain	1.1	2.2	3.2	5.4	19.4	8.6	16.1	15.1	29.0	Comp. strength
Replacement	9.7	7.5	17.2	16.1	24.7	8.6	6.5	4.3	5.4	Slump
Strength gain	4.3	5.4	9.7	7.5	24.7	5.4	23.7	12.9	6.5	Slump
Strength gain	3.2	7.5	7.5	12.9	21.5	7.5	12.9	15.1	11.8	Replacement

Inconsistency	Permeability	Replacement	Slump	Strength Gain
Comp. Strength	⇦ 4.14	⇦ 10.1	⇦ 12.31	⇦ 8.95
Permeability		⇦ 3.83	⇦ 3.87	⇦ 3.71
Replacement			⇦ 2	⇦ 1.98
Slump				⇦ 1.95

Figure 8. Pair comparison matrix from Super Decision program (V3.2).

As shown in Table 4, the comparison scale for each of the two criteria is a number from **1** to **9**, and the evaluator chooses a number from this scale based on how much he prefers

developing characteristic *A* over developing characteristic *B*. When he chooses the number **1**, that means he prefers to develop characteristic *A* by 100% and characteristic *B* by 0%; when he chooses the number **9**, he prefers characteristic *B* by 100% and characteristic *A* by 0%; and when he chooses the number 5, he gives equal weight to developing characteristic *A* and characteristic *B*, resulting in a proportion of 50% for both. The numbers **2, 3**, **4**, **6**, **7**, and **8** are proportionate, as seen in the table below:

Table 4. The choice equivalent of the questionnaire numbers.

Choice	Relative Importance		Difference	Choice Equivalent
	A	B		
(1)	100%	0%	100%	1 *A*
(2)	87.50%	12.50%	75%	0.75 *A*
(3)	75%	25%	50%	0.5 *A*
(4)	65.50%	37.50%	25%	0.25 *A*
(5)	50%	50%	0%	0
(6)	37.50%	62.50%	25%	0.25 *B*
(7)	25%	75%	50%	0.5 *B*
(8)	12.50%	87.50%	75%	0.75 *B*
(9)	0%	100%	100%	1 *B*

Equivalent sum (*A*) = 1 × (∑ Choice **1**)% + 0.75 × (∑ Choice **2**)% + 0.50 × (∑ Choice **3**)% + 0.25 × (∑ Choice **4**)%.
Equivalent sum (*B*) = 1 × (∑ Choice **9**)% + 0.75 × (∑ Choice **8**)% + 0.50 × (∑ Choice **7**)% + 0.25 × (∑ Choice **6**)%.

Super Decisions V3.2 was employed in this study. It is a software package developed for the analysis, synthesis, and justification of complicated decisions using the analytic hierarchy process (AHP) technique [97]. The relative importance of the criteria were inputted, deduced from the previous step, to form a pair comparison matrix, as shown in Figure 8.

In Figure 8, the questionnaire data were evaluated using the aforementioned equation, yielding the following results, such as Criteria (*A*) = 10.1 Criteria (*B*), which can be interpreted as compressive strength (*A*) is preferable to replacement (*B*) by 10.1 times. Compressive strength is still the criterion employed in the market to determine the price of concrete, and as such, it is the influencing factor in either increasing or decreasing the value, with its effect representing 67% of the total weight of all criteria, followed by permeability 19%, 7.4% replacement, 5.4% decline, and 4.5% strength gain.

After the creation of criteria weights and priorities as shown in Figure 9, criteria weights and priorities can be concluded, as shown in Figure 8, which is an output from the program. Here, the idea of "criteria" comes in handy because it figures out what factors have the biggest impact on the product's performance and how customers see its value, as with comparison there is no evaluation [25]. Compressive strength has the highest weight among the other criteria, accounting for 63% of the total weight, and thus requires the most attention to maximize overall value. The ranking is case-specific and should not be used as a template. Comparable products may use the same attributes, but each will have unique characteristics that change the attribute ranking [4].

When measuring "on" criteria, it can be observed that the effects represent the result of the solutions chosen to perform the functions. The criteria are used to quantify the solutions. Because of this, criteria and FAST models are inseparable [4]. Table 5 makes use of results from the AHP analysis, which were calculated with the help of the Super Decision program, shown in Table 2. The data were examined by the program with a friction value of 1. The data in the "totals" column reflect the overall performance of alternatives with a friction value of 1, which indicates the performance of alternatives in terms of previous research results and customer preferences; the numbers above the five "Criteria" columns represent the criteria weights that reflect customer preferences, as shown in Figure 9. Although permeability had the highest performance of all the criteria, its low weight caused it to have a small impact. Instead, compressive strength was found to be the most important and influential performance criterion, with its weight making up 63% of the whole.

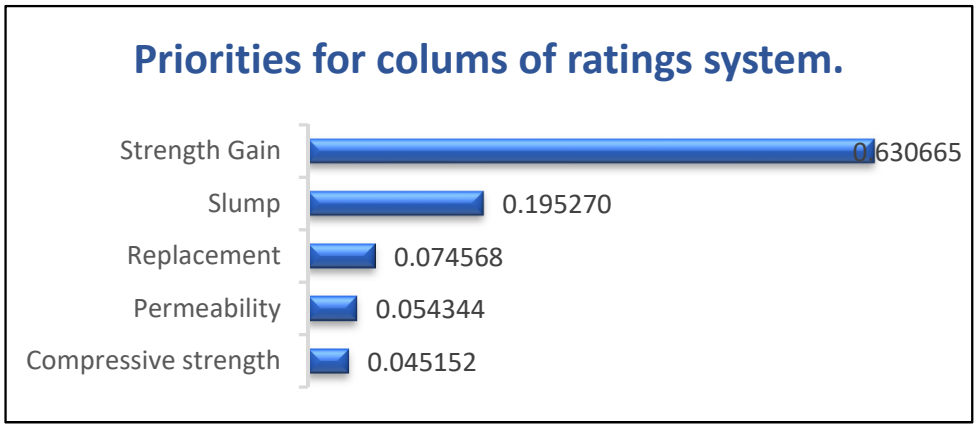


Figure 9. Criteria weights and priorities from the Super Decision program (V3.2).

Table 5. Rating Priorities matrix from the Super Decision program (V3.2).

			0.630665	**0.195271**	**0.074569**	**0.054343**	**0.045153**
	Totals	**Priorities**	**Comp. Strength**	**Permeability**	**Replacement.**	**Slump**	**Strength Gain**
Control	0.078556	0.078555	0.090480	0.062346	0.000001	0.088900	0.099390
5% FA	0.085320	0.085319	0.095450	0.073811	0.018460	0.092400	0.095490
10% FA	0.088146	0.088145	0.095800	0.080869	0.036910	0.090580	0.094390
15% FA	0.090349	0.090348	0.095650	0.086929	0.053450	0.089340	0.093260
20% FA	0.092275	0.092274	0.094990	0.092010	0.072750	0.088670	0.092080
25% FA	0.093630	0.093629	0.093820	0.096093	0.090940	0.088580	0.090850
30% FA	0.094506	0.094505	0.092150	0.099186	0.109120	0.089060	0.089590
35% FA	0.094890	0.094889	0.089960	0.101293	0.127310	0.090100	0.088290
40% FA	0.094796	0.094795	0.087270	0.102409	0.145500	0.091730	0.086950
45% FA	0.094221	0.094220	0.084080	0.102527	0.163690	0.093930	0.085570
50% FA	0.093323	0.093322	0.080370	0.102527	0.181870	0.096700	0.084140

At this stage, all of the previous knowledge was combined by adding the performance of the alternatives for each criterion, as well as the overall performance derived from the AHP study, as shown in Figure 10. It is worth noting that the values and shape of the AHP curve are not matched to any criteria values. It is also clear that some properties have a positive effect while others have a negative effect, but the overall performance derived from AHP is positive, with the highest result correlating to a replacement rate of 35%. However, this is not the end; this performance must be compared to the cost using the VE method. In addition, it can be seen that the compressive strength changed its values to the negative at 33%, but when its criteria weight (67% of the total) was taken into account, it did not change the AHP study's results to the negative. This is the goal of the AHP study, which is a multi-criteria decision analysis technique that looks at the options from all angles.

3.3.2. Quantify Alternatives' Life Cycle Costs (LCC)

The real difficulty arises when considering how to increase the new product's value in light of the rising cost of fly ash. To get the full picture, it is necessary to look at the cost of the product's life cycle because the initial cost provides an incomplete picture, which cannot enable us to make an accurate judgment. VE considers not only the initial price but also the total price paid by the customer over the product's useful lifetime [6].

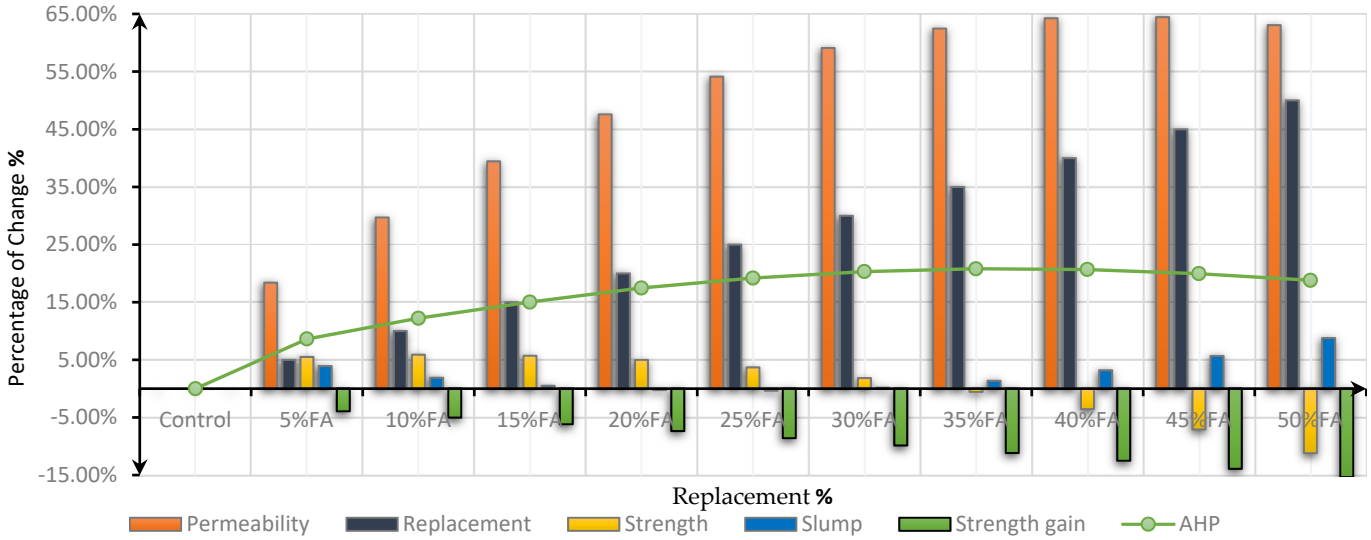


Figure 10. Effect of fly ash replacement on the five comparison criteria and the resultant AHP.

The LCC was calculated from the Egyptian market data on 22 August 2022, with the help of Life-365 V2.2.3 software, which is a standard model developed for predicting the service life and life cycle cost of reinforced concrete exposed to chlorides. The development of Life-365 was paid for by an industry group made up of the National Ready-Mixed Concrete Association, the Concrete Corrosion Inhibitor Association, the Slag Cement Association, and the Silica Fume Associations [98].

In Figure 11, the Life-365 V2.2.3 software inputs for the sample, its size and dimensions, the level of chloride exposure, and the average temperature of the sample environment are shown.

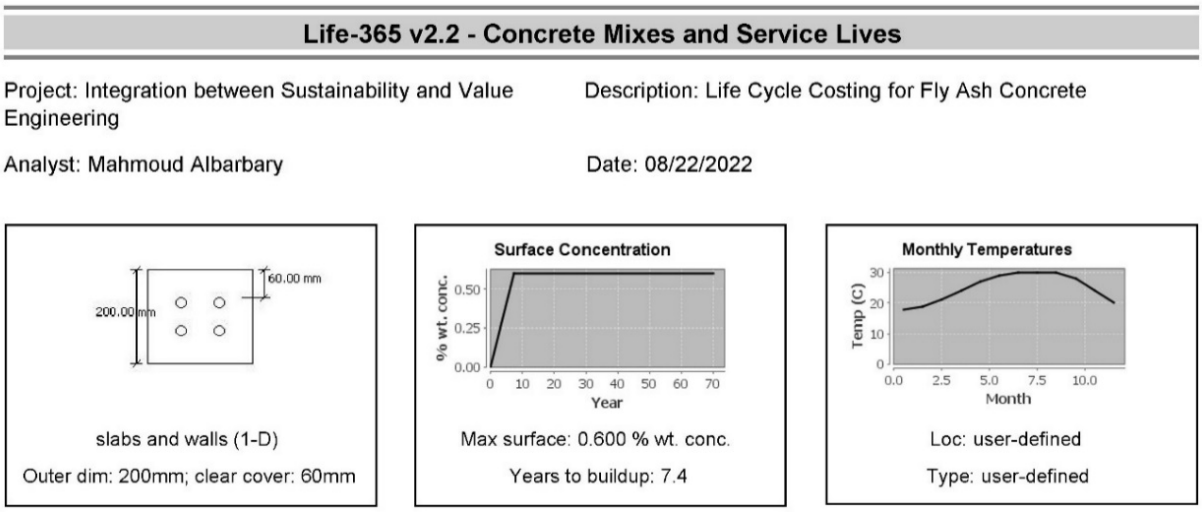


Figure 11. Concrete section and chloride exposure from Life-365 V2.2.3.

Tables 6 and 7 details all of the Life-365 V2.2.3 software inputs and outputs, leading to the main result and output required of this program, which is life cycle costing (LCC).

Table 6. Input data for Life-365 Software.

Project Data			
Name	Value	Name	Value
Date	22 August 2022	January Temp (°C)	18.0
Base Units	SI metric	February Temp (°C)	19.0
Concentration Units (% wt)	% wt. conc.	March Temp (°C)	21.0
Type of Structure	slabs and walls (1-D)	April Temp (°C)	24.0
True Depth (mm)	200	May Temp (°C)	27.0
Service Lile Depth (mm)	200	June Temp (°C)	29.0
Depth to Reinf. (mm)	60	July Temp (°C)	30.0
Third Dim (SQ.m.)	5	August Temp (°C)	30.0
Base Year	2022	September Temp (°C)	30.0
Study Period (years)	70	October Temp (°C)	28.0
Inflation Rate (%)	13.639999999999999	November Temp (°C)	24.0
Discount Rate (%)	18.0	December Temp (°C)	20.0
Location	<user defined>	Area to repair (%)	10
Sublocation	<user defined>	Repair cost ($/sq·m)	190
Exposure Type	<user defined>	Repair interval (yrs)	5
Max Surface Concentration	0.6	Base Mix Cost ($/cub·m)	193.21
Time o buildup (yrs)	7.4		

Table 7. Input and output data for Life-365 V2.2.3.

	Alternatives										
Name	**Control**	**5% FA**	**10% FA**	**15% FA**	**20% FA**	**25% FA**	**30% FA**	**35% FA**	**40% FA**	**45% FA**	**50% FA**
All Description	A project that uses normal mix	A project that uses normal mix	a new description	a new description	a new description	a new description	A project that uses normal mix	a new description	a new description	a new description	a new description
Concrete Mix name	Control	5% FA	10% FA	15% FA	20% FA	25% FA	30% FA	35% FA	40% FA	45% FA	50% FA
w/cm	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Slag (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fly Ash (%)	0.0	5.0	10.0	15.0	20.0	25.0	30.0	35.0	40.0	45.0	50.0
Silica Fume (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Steel type	Black Steel	Black Steel	Black Steel	Black Steel	Black Steel	Black Steel	Black Steel	Black Steel	Black Steel	Black Steel	Black Steel
Steel %	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Propagation (yrs)	6	6	6	6	6	6	6	6	6	6	6
Inhibitor	<none>	<none>	<none>	<none>	<none>	<none>	<none>	<none>	<none>	<none>	<none>
Barrier	<none>	<none>	<none>	<none>	<none>	<none>	<none>	<none>	<none>	<none>	<none>
D28 (m'misec)	8.8716×10^{-12}	8.8716×10^{-12}	8.8716×10^{-12}	8.8716×10^{-12}	8.87×10^{-12}	8.87×10^{-12}	8.8716×10^{-12}	8.8716×10^{-12}	8.87×10^{-12}	8.87×10^{-12}	8.8716×10^{-12}
m	0.2	0.24	0.28	0.32	0.36	0.4	0.44	0.48	0.52	0.56	0.6
Initiation(yrs)	7.2	7.9	8.9	10.1	11.6	13.6	16.2	19.8	24.8	31.8	40.9
Propagation (yrs)	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Service Life (yrs)	13.2	13.9	14.9	16.1	17.6	19.6	22.2	25.8	30.8	37.8	46.9
Use user mix cost	false	true	true	true	true	true	true	true	true	true	true
User Mix Cost.	193.211	197.04	200.89	204.73	208.56	212.0	216.0	220.0	223.0	227.0	231.0
Repair interval	5	5	5	5	5	5	5	5	5	5	5
Base Cost ($)	$193	$197	$201	$205	$209	$212	$216	$220	$223	$227	$231
Barrier Cost ($)	$0	$0	$0	$0	0%	0%	0%	0%	0%	0%	0%
Repair Cost ($)	$304	$304	$293	$265	$255	$237	$205	$176	$139	$101	$60
Life-Cycle Cost ($)	$497	$501	$494	$470	$464	449	$421	$396	$362	$328	$291

The implemented solutions (alternatives) are what VE evaluates, not functions. This dimensional approach is intended to establish a comparative relationship of the cost to perform functions rather than to produce an exact cost estimate [4]. The data in Figure 11 show information about sample data and chloride exposure, while Tables 6 and 7 show data inputs and outputs in detail. Looking at the previous results in Table 8, it is seen that the construction cost (CC) of concrete increases with the proportion of cement replacement with FA due to its higher price compared to Portland cement, which causes customers to be hesitant to buy this product. However, when looking at LCC, it is seen that it decreases as the replacement rate increases due to the increase in its durability compared to Portland cement, which makes it need low maintenance cycles across the product's life, which motivates the client to use the product.

Table 8. Construction cost and life cycle cost from Life-365 V2.2.3.

	Life-Cycle Costs			
Name	**Construction Cost**	**Barrier Cost**	**Repair Cost**	**Life-Cycle Cost**
Control	$193	$0	$304	$497
5% FA	$197	$0	$304	$501
10% FA	$201	$0	$293	$494
15% FA	$205	$0	$265	$470
20% FA	$209	$0	$255	$464
25% FA	$212	$0	$237	$449
30% FA	$216	$0	$205	$421
35% FA	$220	$0	$176	$396
40% FA	$223	$0	$139	$362
45% FA	$227	$0	$101	$328
50% FA	$231	$0	$60	$291

4. Results and Discussion

With the information in hand, the benefits of using fly ash concrete to those of using traditional concrete can be compared by calculating the value based on both the initial cost and the life cycle cost, and by highlighting the alternative with the highest value using the value equation Value = Performance/Cost, as shown in Table 9.

Table 9. Value calculations based on construction cost (CC) and life cycle cost (LCC).

Alternatives	**According to the AHP Results**			**According to the Construction Cost**				**According to the Life Cycle Cost**			
	AHP Results	**Change in AHP Results (%)**	**Rank**	**Cost (CC)**	**Value (V.CC)**	**Change in Value (%)**	**Rank**	**Cost (LCC)**	**Value (V.LCC)**	**Change in Value (%)**	**Rank**
Control	0.828	0.00%	**11**	193	0.004	0.00%	**11**	497	0.002	0.00%	**11**
5% FA	0.899	8.57%	**10**	194	0.005	8.02%	**9**	501	0.002	7.71%	**10**
10% FA	0.929	12.20%	**9**	201	0.005	7.73%	**7**	494	0.002	12.88%	**9**
15% FA	0.952	14.98%	**8**	205	0.005	8.25%	**5**	470	0.002	21.58%	**8**
20% FA	0.972	17.39%	**7**	209	0.005	8.40%	**3**	464	0.002	25.74%	**7**
25% FA	0.987	19.20%	**5**	212	0.005	8.52%	**1**	449	0.002	31.95%	**6**
30% FA	0.996	20.29%	**3**	216	0.005	7.48%	**2**	421	0.002	42.00%	**5**
35% FA	1	20.77%	**1**	220	0.005	5.95%	**4**	396	0.003	51.58%	**4**
40% FA	0.999	20.65%	**2**	223	0.005	4.42%	**6**	362	0.003	65.65%	**3**
45% FA	0.993	19.93%	**4**	227	0.004	1.96%	**8**	328	0.003	81.72%	**2**
50% FA	0.983	18.72%	**6**	231	0.004	-0.81%	**10**	291	0.003	102.76%	**1**

Table 9 ranks the alternatives based on three different considerations: (1) the results of AHP; (2) the value based on the construction cost; and (3) the value based on the life cycle

cost, all of which reflect the percentage of change in performance compared to conventional concrete. The ranking is not equal for the alternatives for the three scenarios, but they agree on one thing, which is that the performance of conventional concrete is the worst. The results of the AHP study indicate that a 35% replacement rate is the best alternative, whereas a 25% replacement rate and a 50% replacement rate, respectively, are the best alternatives according to construction cost-based value and life cycle cost-based value, respectively. It is compelling evidence that a more comprehensive approach, including market research, is required for assessing a property's value. When studying the results of the AHP, it does not provide us with accurate results as it is the result of a purely technical study that takes into account customer preferences. Similarly, studying the value resulting from the construction cost does not provide an accurate picture 100% of the time, but studying the value based on the life cycle cost provides an accurate picture that can be relied upon, as well as one that shows the strength of these alternatives and opens a market space for them by indicating their points of strength. The change in cost can be observed in Figure 12. While the construction cost rises gradually until it reaches a 20% increase at the 50% replacement rate, the life cycle cost falls gradually until it reaches a 41.45% reduction at the 50% replacement rate. The change in value can also be deduced from Figure 12, whether using construction cost or life cycle cost, where it can be observed that the value has doubled when 50% of fly ash is used as a substitute for Portland cement. While the corresponding value of the construction cost is examined, it can be concluded that the growth is modest until it reaches the maximum value at a replacement rate of 25%; even then, it does not exceed 8.5% and it then returns to zero. It is important to calculate its value according to its life cycle, not just its construction cost.

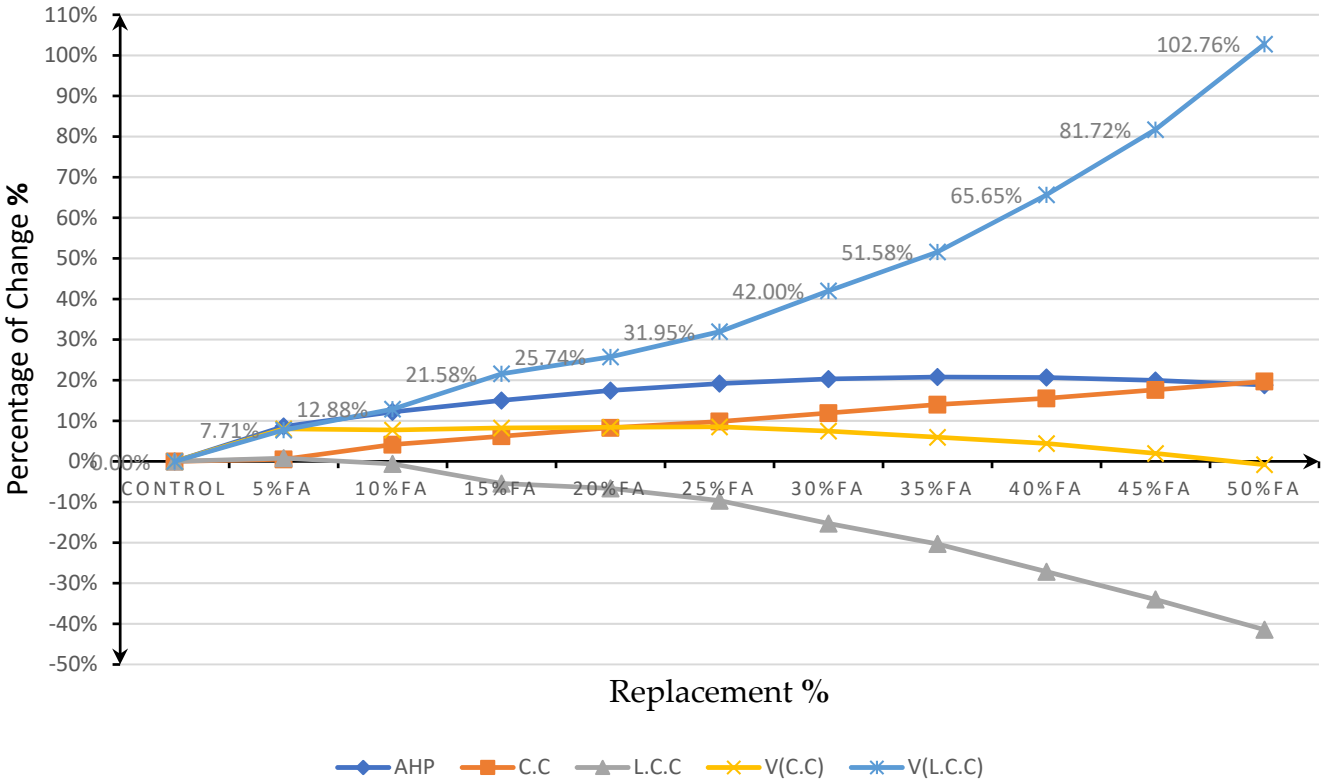


Figure 12. Effect of FA replacement on the resultant AHP, construction cost (CC), life cycle cost (LCC), construction cost-based value (V.CC), and life cycle cost-based value (V.LCC).

5. Conclusions

This research is of great importance in the practical field, as it helps to solve the basic problem of changing concrete conceptually from a material based on nonrenewable

resources to one that provides value to waste materials of low immediate value that are typically an environmental concern, and it will move away from using solely Portland cement clinker-based to a more general hydraulic binder industry, reducing CO_2 emissions. Based on the analysis's findings, the following primary conclusions can be drawn from this study:

- This research offered an applicable framework for evaluating concrete and determining the degree to which the market is willing to accept any change in the concrete components. The framework's data are case-specific since the best and most sustainable solution in one case may not be the best in another. The average trend was evaluated from 42 previous studies instead of the best or worst results for the criteria. Thus, the sample's quality can influence results and its corresponding value. Using high quality materials makes the product easier for buyers to accept.
- The desired outcome was achieved by replacing a portion of the Portland cement with FA. This showed that using sustainable materials increases the value of concrete, which makes these materials more appealing to buyers as they are worth more and give them the best return on their money. This grew concrete's market and enabled us to reach the desired conclusion.
- Durable concrete saves money over its lifetime. There was a gradual increase in construction costs up to 20% at a percentage of replacement of 50%, but there was a significant reduction in life cycle costs down to a decrease of 41.45% compared to conventional concrete. The rationale behind this is lengthening the service life and reducing maintenance costs.
- The value increases two-fold when half of the Portland cement is replaced by fly ash, while the study of the corresponding value of the construction cost reveals that the growth is modest as it does not exceed 8.5% at a 25% replacement rate and then returns to zero. This clearly demonstrates that in order to obtain true and representative results, the study of value must consider the life cycle cost over the initial cost.
- It is important to ensure that the value study is not a technical study but rather a customer-oriented study in the first place, because the performance data generated by AHP analysis are not indicative of value as its curve has a different shape than the value curves generated when studying the cost of construction or life cycle. Furthermore, the best alternative according to AHP results (35% FA) was not the best alternative according to CC (25% FA) or LCC (50% FA) analysis.
- The small value of the regression coefficient between the FA percentage rate and the other criteria indicates that there is no stable relationship between the two variables. The wide range of results was attributed to the different compositions of FA and its source.

Through the results of the research, it is suggested that the following points be studied in future research:

- Customer requirements are a direct indication of the relative weights of the various criteria. Marine concrete, for instance, needs to be impermeable and resistant to chlorides. Dams' hydration temperature control is crucial. Thus, the same concrete mixture has different values depending on the purposes for which it is used. This opens the door for VE to be used as a tool to adjust components to fit specific needs according to customer preferences and give him or her the highest return on their investment in concrete.
- The framework presented in this study can be reused to evaluate concrete and figure out how much the market is willing to accept any changes to its components: not only fly ash, but also other supplementary cementitious materials, alternative aggregate, and any additives added to concrete or any change in the mix.

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