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Impact of Self-compacting Concrete Design with Application of Micro Silica and Plasticizer on Workability, Cost and Strength

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Abstract Self-compacting concrete offers significant advantages in infrastructure projects, but its application in specific regions such as Junín has not yet been widely studied. The research evaluates the design of self-compacting concrete with microsilica and plasticizer, focusing on its workability, cost and strength. Using a mix with type I cement, 5-10% silica fume and SikaCem, workability and strength tests are performed. The purpose is to determine the economic feasibility and technical advantages of self-compacting concrete compared to conventional concrete. The results show excellent flowability and passability, with a flow time in the V-funnel of 10.8 seconds and a blocking coefficient of 0.9, complying with regulations. Strength tests reveal values of 407.3, 426.5 and 437.9 kg/cm² at 7, 15 and 28 days. Although the initial cost is higher ($120/m³), the cost-benefit analysis highlights a 17% reduction in construction time, with savings in labor and maintenance, and greater durability. The cost/benefit ratio of 1.2061 indicates that self-compacting concrete is economically favorable and efficient for complex construction. The conclusions highlight that, although the initial cost of self-compacting concrete is higher, the long-term savings and advantages in terms of quality and durability justify its adoption. It presents a better understanding of the economic and technical impacts of self-compacting concrete, providing a solid basis for its implementation in infrastructure projects in the region by considering local variables in the analysis, which offers a contextualized perspective relevant to the specific conditions of the area. This study underscores the importance of innovating in construction materials to improve efficiency and sustainability in the industry.

Keywords Concrete, Design, Cost-Benefit, Structures, Workability

1. Introduction

Concrete has been one of the fundamental pillars in the evolution of civilization, from ancient Roman structures to the modern skyscrapers that define urban skylines around the world [1]. Its versatility, durability and ability to adapt to various shapes and structures make it an essential material in civil construction [2]. Globally, innovation in concrete design and application is enabling humanity to reach new limits in engineering and architecture, driving the development of safer, more sustainable and resilient infrastructures [3]. This journey of concrete over time begins millennia ago and continues to evolve with new technologies and approaches that seek to improve its properties and applications.

In first world countries, the variety of concretes used is as diverse as the needs they must satisfy. From reinforced and prestressed concrete used in bridges and high-rise buildings, to self-compacting and high-strength concretes that allow for more efficient and faster construction [4]. Each type of concrete has a specific purpose, adapting to the climatic, geographic and infrastructure requirements of each nation [5]. In first-world countries, investment in research and development has led to the creation of specialized mixes that improve not only the strength and durability of the material, but also its environmental sustainability [6] [7].

In Peru, the application of concrete in construction is of vital importance for the economic and social development of the country [8]. The geographical and seismic characteristics of the Peruvian territory demand the use of construction materials that are not only strong and durable, but also adaptable and safe [9]. The implementation of advanced concretes in urban and rural infrastructure projects can mean a significant improvement in the quality of life of its inhabitants, generating buildings that are more resistant to natural disasters and with long-term sustainability [10]. In addition, self-compacting concrete, with its ability to fill complex forms and confined spaces without the need for mechanical vibration, offers an efficient and effective solution for construction in hard-to-reach areas [11].

Ready-mix concrete has become an essential component in modern construction due to its convenience and controlled quality. As it is produced in specialized plants, it allows for greater precision in the dosing of materials, ensuring homogeneous and consistent mixes [12] [13]. Its application is wide, ranging from small residential works to large infrastructure projects. The importance of ready-mix concrete lies not only in improving efficiency and reducing construction times, but also in reducing waste and environmental impact, crucial aspects in a world that is increasingly seeking sustainability [14].

In the present research, the impact of self-compacting concrete design with the addition of micro silica and plasticizer on three fundamental aspects: workability, cost and strength is explored. The objectives of this research include the design and evaluation of how these additions can improve the flowability and compaction of concrete [15], reduce the costs associated with labor and vibration equipment, and test the increase in durability and strength of the design subjected to flexocompression tests [16]. The importance of this study lies in the possibility of developing more efficient and economical concrete solutions that respond to the needs of a constantly evolving construction sector, both in Peru and in the rest of the world.

2. Materials and Methods

The research proposal focuses on analyzing the design of self-compacting concrete, capable of flowing under its own weight through large amounts of steel or dense corrugated reinforcing steel, as well as complex surfaces in structural elements, poured in complex geometries and inaccessible or difficult to vibrate places. The design considers materials capable of complying with international standards, achieving a concrete capable of filling all voids without causing segregation or bleeding in the pour.

Type I cement is used, obtained by grinding Type I clinker and gypsum, with a density of 3.15 g/cm^3. This cement acquires compressive strengths of 274 kg/cm^2 at 3 days, 340 kg/cm^2 at 7 days and 440 kg/cm^2 at 28 days [17], exceeding the minimum requirements for Type I concrete and the cement test methods of NTP-334.009, UNE-EN 197-1:2011 and ASTM C-150.

The improvement of the characteristics of self-compacting concrete is through the implementation of admixtures recommended by experts worldwide, which suggests the use of chemical elements. In this context, a pozzolanic admixture [18] and a superplasticizer [19] are used to guarantee the desired properties of the concrete. The superplasticizer admixture used, SikaCem, is a chloride-free plasticizer, dosed at a rate of 500 ml per 42.5 kg bag of cement. This product, with a density of 1.2 g/cm^3, is composed of a mixture of lignosulfonates and organic polymers.

In addition, powdered silica fume [18], with a dosage of 5% to 10% of the weight of the cement and a density of 0.65 g/cm^3, is incorporated. This additive, based on silica fume technology, is composed of silicon dioxide and complies with ASTM C 494 and EN 934.

2.1. Aggregates

Aggregates play a fundamental role in the concrete industry as essential components that provide mechanical strength and dimensional stability to the material. These aggregates comply with the necessary specifications for mix design and testing, as well as with NTP 400.037:2000, which establishes the quality of fine and coarse aggregates for use in concrete. These aggregates are extracted from the department of Jun ń, located in Peru, which plays a crucial role in construction due to its availability and quality.

Table 1. Aggregate testing

Description	Fine Aggregate	Unit	Coarse Aggregate	Unit
Dry loose unit weight	1.68	gr/cm ³	1.48	gr/cm ³
Dry compacted unit weight	1.81	gr/cm ³	1.57	gr/cm ³
Dry mass specific weight	2.56	gr/cm ³	2.62	gr/cm ³
Moisture content	3.591	%	0.647	%
% of Absorption	2.03	%	1.304	%
Finesse Modulus	3.159		6.643	

Tests performed to evaluate the properties of the aggregates include the measurement of the dry loose and dry compacted unit weight, determining the bulk density of the aggregate in the loose and compacted states, respectively. The specific dry mass weight is also determined using the pycnometer method to calculate the relative density of the dry aggregate. The moisture content is measured by drying a sample of the aggregate in an oven and calculating the percentage of water present, while the percentage absorption is evaluated by immersing a dry sample in water and measuring the mass gain [20]. These tests are carried out according to standardized procedures to ensure the reliability of the results, which are presented in Table 1.

2.2. Mix Design

The data obtained from the tests of the materials extracted in Jun ń will be fundamental for the definition of the mix design of the self-compacting concrete. These results will provide us with detailed information on the physical and chemical properties of the aggregates, as well as the cement and admixtures used. Based on this data, we will be able to adjust the proportions of each component to optimize both the workability of the concrete during placement and its final strength once it has set.

In addition, another crucial aspect that we will address is the water-cement ratio (w/c). This ratio is determinant in controlling cement hydration and, therefore, in influencing the final properties of the concrete, such as its strength, durability and permeability. Through a thorough analysis of the w/c ratio, we seek to find the optimal balance that ensures a sufficiently fluid mix for self-compacting, but without compromising its long-term structural bearing capacity. The design in terms of strength aims to achieve a value of 350 kgf/cm ², according to the guidelines proposed by ACI committee 211, for the appropriate dosages [21]. This mix design method, applied for 1m ³, made it possible to determine the precise quantity of each material, as detailed in Table 2 of the study.

Table 2. Material Quantity Dosing - Mix Design

Materials	Weight or mass	Volume
Cement	692.77 kg	0.22 m ³
Water	207 kg	0.20 m ³
Sand	549.75 kg	0.21 m ³
Stone	813.69 kg	0.31 m ³
SikaCem Plasticizer	7.01 kg	0.005 m ³
Microsilica additive	59.58 kg	0.027 m ³

2.3. Workability Tests

For workability testing, several recognized methods are evaluated to measure and ensure adequate flowability and capacity of self-compacting concretes [22]. These methods include the V-funnel box, U-funnel box, L-funnel box and the standard Abrahams cone method which are fundamental to evaluate the flow and filling capacity of fresh concrete [23]. These tests provide crucial data that allow adjustment of mix material proportions to optimize workability and ensure that the concrete can completely fill complex forms and structures without segregation or over-compaction.

2.3.1. V-Funnel Box

The purpose of the test is to evaluate the flowability of concrete in restricted areas in the vertical direction and under its own weight, analyzing the quality and tendency to segregation and blocking as shown in Figure 1. During the test, the variation of the flow velocity is visually verified to determine these aspects.

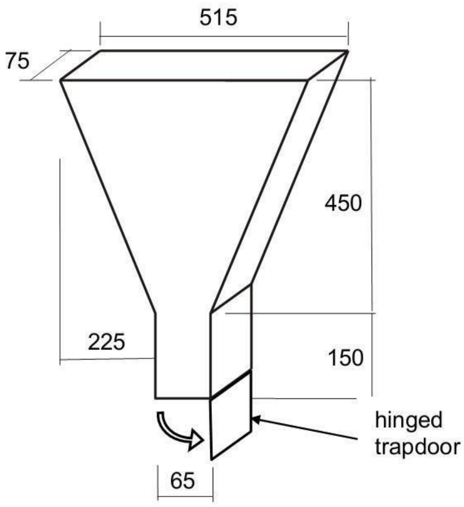

Figure 1. V-Funnel Box

2.3.2. Box U

The U-box test measures the passing ability and ease of filling of self-compacting concrete, providing a critical evaluation of its behavior under tight confining conditions. This test simulates situations where concrete must flow through dense reinforcement or complex shapes, evaluating its ability to completely fill voids without segregating or blocking as shown in Figure 2.

2.3.3. Box L

The L-box test measures the ability of self-compacting concrete to pass through densely spaced reinforcing bars, simulating actual construction conditions where concrete must flow without obstruction. The L-box configuration, as shown in Figure 3, consists of an L-shaped channel with a set of reinforcing bars at the corner of the curve. During the test, concrete is poured into one end of the channel and allowed to flow by gravity through the bars to the other end.

For a self-compacting concrete to pass the workability evaluation criteria, it must comply with Table 3. This table details the essential parameters, including flowability, fillability, and the ability to pass through dense reinforcement [24]. Specifically, the reference values for the Abrahams cone, U-box, L-box and V-funnel tests should be within the established ranges to ensure that the concrete maintains its cohesion and homogeneity without segregating or blocking during the pouring process.

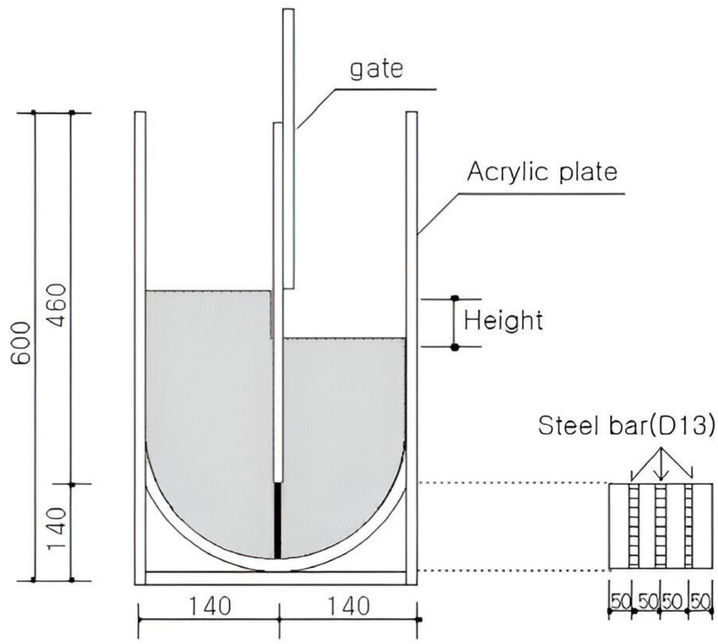

Figure 2. Box U

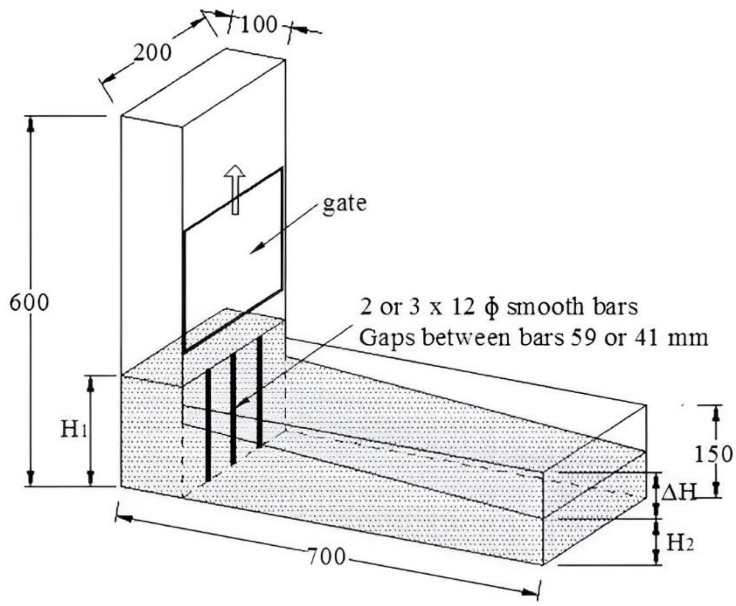

Figure 3. Box L

Table 3. Workability Test Tests [24]

Features	Test Method	Specification	Class	Values
Workability	Slump flow test	Settling flow (mm)	SF1	550 to 650 mm
			SF2	660 to 750 mm
			SF3	760 to 850 mm
Viscosity (flow rate)	T500 (slump flow) or V-funnel test	T500 in s V-funnel time	VS1/VF1	≤2 s / ≤8 s
			VS2/VF2	>2 s / 9 to 25 s
Passage capacity	L-box test	Passage capacity	PA 1	> 0.8 for 2 bars
			PA 2	≥ 0.8 with 3 bars
Segregation	Segregation resistance test (sieve)	% segregation resistance	SR1	≤ 20%
			SR2	≤ 15%

2.4. Mechanical Tests

Mechanical tests performed on self-compacting concrete provide essential data on its behavior and strength under loading conditions. The results of these tests show the axial stress data of the concrete samples, known as specimens, at 7, 15 and 28 days of curing [15]. Such test is performed by extracting cylindrical specimens with dimensions of 6" in diameter and 12" in height in the concrete compression breaking press machine, shown in Figure 4, for their respective axial compressive strength tests at a normalized constant speed. These tests allow evaluating the strength evolution of the self-compacting concrete over time, providing critical information to ensure that the material meets the structural and durability requirements expected for its application on site.

Figure 4. Specimen Compression Machine

2.5. Cost/ Benefit

The cost-benefit analysis of the use of self-consolidating concrete (SCC) on site reveals clear advantages in both the short and long terms. Although the initial cost may be higher due to the inclusion of specialized admixtures, such as superplasticizers and microsilica, and high quality materials, the cumulative benefits significantly outweigh these initial costs. Key benefits of SCCs include:

- **Reduced execution time:** By eliminating the need for manual vibrating and compaction, pouring is accelerated and allows for faster placement, reducing jobsite execution times.
- **Reduced labor demand:** The automation of the compaction process and the improved flow of the SCC reduce the number of personnel required on site.
- **Minimization of structural defects:** Thanks to its high flowability and ability to fill formwork with complex geometries and dense rebar without segregation, the risk of defects such as voids or porosities is significantly reduced, thus minimizing subsequent repair costs.
- **Superior durability:** SCC provides higher density and strength, which contributes to the extended service life of structures, reducing long-term maintenance costs.

Therefore, the implementation of self-compacting in-situ concrete represents an economical and beneficial option in the long term [16]. For the calculation of the cost/benefit of using self-compacting in-situ concrete, equation 1 can be used.

$$\text{Cost/Benefit Ratio (CBI)} = \frac{\text{Total Costs}}{\text{Total benefits}} \qquad (1)$$

To correctly evaluate the cost/benefit ratio (CBI) of using self-compacting concrete on site, it is important to keep in mind that a CBI value greater than 1 indicates that the benefits exceed the costs, which is the desired outcome.

To quantify the cost/benefit (CBI) of self-compacting concrete, it is essential to break down the Total Costs and Total Benefits. How to calculate both is detailed below:

Total Costs (TC):

- **Cost of materials:** It includes the price of cement, aggregates, admixtures (superplasticizers and microsilica) and water. It is important to consider the increased cost of admixtures compared to conventional concrete**.**
- **Cost of specialized equipment:** In some situations, additional equipment may be required, such as specialized concrete pumps for SCC placement.
- **Transportation and logistics costs:** Especially on large-scale construction sites, the cost of transporting materials must be included.
- **Preparation and laboratory testing costs:** These include testing for workability, viscosity, and compressive strength to ensure the quality of the concrete.

Total Benefits (BT):

- **Reduced construction time:** The reduction in execution time, due to the elimination of vibrating, reduces overall construction time, which can translate into lower operating costs.
- **Reduced labor:** By requiring fewer personnel for placement and compaction, labor costs are reduced.
- **Reduced risk of defects and maintenance:** Due to their high durability, structures built with SCC have less need for long-term repairs and maintenance.
- **Increased durability:** SCC contributes to a longer service life of the structure, generating long-term savings due to less frequent maintenance or structural rehabilitation.

Where Total Costs include all costs associated with the implementation of the self-compacting concrete, such as the costs of materials, admixtures and any specialized equipment needed.

3. Results

To evaluate the performance of self-compacting concrete, with a particular focus on its workability, compressive strength and cost/benefit analysis, it is necessary to develop a comprehensive methodology that encompasses the selection and preparation of materials, the performance of workability and strength tests, and an economic analysis with respect to the benefit of implementation.

The present investigation begins with the selection of suitable materials, including fine and coarse aggregates extracted from the region of Jun ń, Peru, and the use of admixtures such as microsilica and superplasticizers to improve the properties of the self-compacting concrete. Workability tests, such as the U-box, L-box and V-funnel, are carried out to evaluate the flow and filling capacity of the concrete under restricted conditions. Subsequently, mechanical tests are performed to measure the compressive strength of concrete at different curing ages, using standard specimens and a concrete break press machine. Finally, a cost/benefit analysis is carried out to evaluate the economic feasibility of using self-compacting concrete on site.

3.1. Workability Tests

These tests measure the concrete's ability to move and fill complex forms without segregation or blocking. The results indicate that the self-compacting concrete has excellent flowability and stability, meeting the workability parameters in Table 3 for applications in highly complex structures, thus ensuring its effectiveness in demanding construction conditions.

3.1.1. V-Funnel Box

In the V-funnel test, the flow time of the fresh mix was 10.8 seconds, which is within the recommended range of 6 to 12 seconds according to the EFNARC standard. This result suggests an adequate viscosity to ensure gap filling in complex structures. However, it is important to note that, although the flow time meets the standard parameters, further analysis of the rheology of self-compacting concrete would indicate the influence of plastic viscosity and yield strength. These factors are critical to ensure that the concrete maintains its cohesion without compromising its self-leveling ability during the placement process.

In the flow extension test, no segregation is observed and the visual stability indices are 0. The time required to reach a diameter of 50 cm due to gravity slump is 5 seconds, which suggests an optimum viscosity (VS1/VF1), as it is in the range of 2 to 10 seconds specified by ASTM C1611/C 1611M.

Figure 5 shows the performance of the corresponding test, obtaining the mentioned results. The cementitious paste covers and envelops the aggregates without water or slurry escaping, indicating good cohesion. The mix obtains a runoff flow value between 65 cm and 80 cm and the slump is between 660 mm and 750 mm corresponding to a SF2. A slump flow of less than 50 cm is insufficient to pass through highly reinforced structures, while a flow of more than 70 cm risks segregation and heterogeneity, which is not suitable for reinforced concrete.

(a) (b)

Figure 5. Box V. (a) Concrete poured and screeded in box V, (b) Exit of concrete through box V

It is worth mentioning that the distance of the flow extension was 70 cm being a category A flow for gravel with a maximum nominal size of ¾" as established by ASTM C 1611/C 1611M.

3.1.2. Box L

In the L-box test, the blockage coefficient is found to be 0.9, which represents the ratio between the heights of the fill at the end of the mold and the full fill of the concrete as it exits and flows through the rebar. This value indicates adequate flow with minimal risk of blockage of the gravels between the three rebars.

The self-compacting concrete demonstrates excellent workability and adequate viscosity, meeting the criteria established by the relevant standards. These results, visualized in Figure 6, confirm that the self-compacting concrete mix behaves optimally in terms of flow and cohesion, guaranteeing its effectiveness for applications in complex and highly reinforced structures.

(a) (b)

Figure 6. Box L. (a) Concrete flow through box L, (b) Measurements of concrete in box L

3.2. Mechanical Tests

The test results show the axial stress values obtained from concrete specimens at different curing ages, as presented in Table 4. These data provide a detailed view of the strength development of self-compacting concrete over time. Table 4 includes specific compressive strength measurements at intervals of 7, 14, and 28 days of curing. These data are critical to understanding how self-compacting concrete acquires its structural strength and how it responds to standard curing conditions. The detailed information in the table allows you to identify patterns of behavior and compare them to regulatory and structural design requirements.

Table 4. Compressive Strength Test Results

N °of Tests	f'c kg/cm^2		
	7 days	15 days	28 days
Test 1	407.3	426.5	437.9
Test 2	410.6	435.3	455.3
Test 3	412.8	457.3	470.6

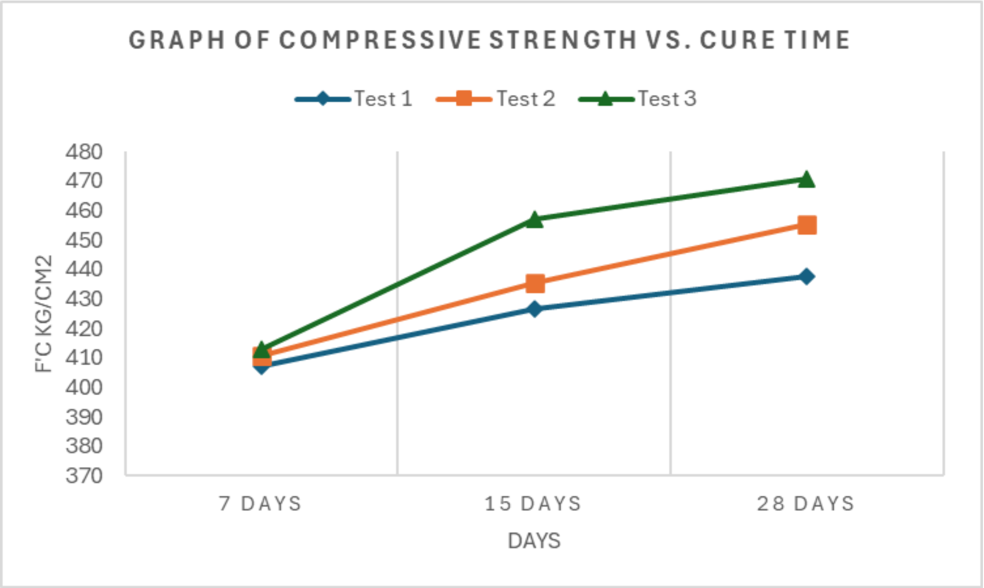

Figure 7. Acquired resistances at 7, 15 and 28 days

In addition, the results are shown in Figure 7, which visually illustrates the compressive strength measurements at different curing intervals. Figure 7 provides a graphical representation of how self-compacting concrete develops its strength over time, facilitating a more intuitive understanding of its mechanical performance. These results allow engineers and construction professionals to make informed decisions about the suitability of this type of concrete for specific projects, ensuring that safety and durability standards are met.

3.3. Cost/ Benefit

The cost/benefit of the use of self-compacting concrete will be given by contracting 152 m^3 for the pouring of a large building. A calculation of the benefits of implementing the use of self-compacting concrete is stipulated, which estimates a 17% savings in construction time due to the efficient flow and filling capacity of the concrete, equivalent to $5,000 in labor and scheduling costs (B1). In addition, by eliminating the need for vibrating and reducing labor for manual compaction, an additional $6,000 in savings is estimated (B2). Premature maintenance costs estimated at $1,000 per year are expected to be avoided, totaling $5,000 over the slab life (B3) of 5 years. The increased durability of self-compacting concrete also reduces long-term maintenance costs, with an estimated savings of $6,000 (B4). In terms of cost, self-compacting concrete through procurement from a tertiary company costs $120 per m^3, resulting in a total of $18,240 for 152 m^3 (C1). This data analysis and assumptions are detailed in Table 5, which describes the economic benefits derived from the use of self-compacting concrete with respect to the acquisition cost of self-compacting concrete [25].

Table 5. Benefits and Costs

Code	Description	Total Price
B1	Reduction in construction time	$5,000.00
B2	Reduction in labor	$6,000.00
B3	Reduced risk of defects and maintenance	$5,000.00
B4	Increased durability	$6,000.00
C1	Autocompact Concrete Cost	$18,240.00

The cost/benefit analysis presents a detailed summary of the total expected benefits and costs associated with the use of self-compacting concrete in a structure by contracting 152 m^3. The total benefits, which include savings in construction time, labor, maintenance, and increased durability, total $22,000.00. On the other hand, direct material costs specific to self-compacting concrete are estimated at $18,240.00. The calculated benefit-cost index (BCI) is 1.2061.

Table 6. Cost/Benefit Ratio (BCI)

Description	Total Price
Total Benefits (B1+B2+B3+B4)	$22,000.00
Total Costs (C1)	$18,240.00
Cost/Benefit Ratio (BCI)	1.2061

4. Discussion of Results

Based on workability tests, it is determined that the present design has a workability of Class SF2 with a continuous and uniform flow, which is suitable for filling complex structures and dense reinforcing bars. The viscosity is classified as VS1/VF1 with a passability of

Class PA2 and an optimum filling coefficient of 0.93 with 3 bars, minimizing the risk of segregation (Class SR1). These results underline the importance of optimal design to ensure the flowability and homogeneity of self-compacting concrete, guaranteeing efficient placement and reducing the risk of defects during construction.

The resistance evidences that the first test results at 7 days showed promising figures, reaching 117.21% of the required average resistance of 350 kg/cm^2, thanks to the inclusion of the superplasticizer additive. At 15 days, the average strength reached 126% of the required strength, and in the final results, the average exceeded 130%. This indicates that the self-compacting concrete developed exceeded expectations in terms of compressive strength, demonstrating that the addition of appropriate admixtures and optimal self-compaction results in more robust and durable concrete.

The calculated benefit-cost index (BCI) is 1.2061, which indicates an index greater than 1 and confirms that the benefits outweigh the costs. This suggests that the use of self-compacting concrete in this context is economically favorable and justifies the initial investment, compared to conventional or ready-mixed concretes. The combination of improved workability, strength, and cost efficiency positions self-compacting concrete as a viable and cost-effective option for structural applications that require high standards of performance and durability.

5. Conclusions

The results of this research demonstrate that self-compacting concrete (SCC) offers significant benefits in terms of workability, strength, and cost. In particular, Class SF2 workability, combined with optimized viscosity and flowability, was found to allow efficient filling of complex structures, minimizing the risk of segregation. This advantage is particularly relevant for civil engineering projects requiring precise placement in hard-to-reach areas or in densely reinforced structures.

In terms of strength, the CAC consistently exceeded expectations, reaching 130% of the required strength at 28 days. This highlights one of its main advantages: its long-term structural robustness. However, one of the challenges it presents is its higher initial cost compared to conventional concretes, which could be a disadvantage for projects with limited budgets. Even so, the cost-benefit analysis (BCI = 1.2061) showed that, in the long term, the savings in labor, construction time and maintenance reduction compensate the initial investment, justifying its use. Therefore, it shows its importance in the area of civil engineering, since it optimizes construction processes by eliminating the need for vibrating and reducing the labor required for manual compaction. In addition, it improves the efficiency of construction time and reduces the costs associated with long-term maintenance of structures.

This research proposes to engineers around the world to evaluate the use of self-compacting concrete and make correct designs that maximize structural durability and construction efficiency by having an optimal mix design and its importance of the use of superplasticizing admixtures and micro silica in the improvement of construction products. This will benefit the understanding of the use of self-compacting concrete generated with superplasticizing admixtures and microsilica admixtures in the reduction of operating costs, shorter construction times and longer service life of infrastructures.

Future research is expected to further explore the possibilities for improvement in mix formulation, the application of new admixtures and emerging technologies for self-compacting concrete. In addition, further studies are needed to evaluate the long-term performance and environmental sustainability of these innovative materials in different contexts and climatic conditions.

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