

Evaluation of Mechanical and Durability Properties of Sustainable Concrete using Building Debris and Silica Fume

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Abstract. With rising demand for construction materials, alternative materials are becoming increasingly important for long-term growth. The growing societal push for a sustainable, green environment has prompted engineers to seek alternative materials to mitigate the negative impacts of concrete structures. The primary goal of the study is to determine the strength and durability of concrete by using recycled building debris to replace a portion of the coarse aggregate and by incorporating silica fume as a supplementary cementitious material. This incorporates mix designs with 20%, 40%, and 60% building debris and 5%, 10%, and 15% silica fume replacement. Compressive strength was tested at 7, 28, and 90 days. Durability tests include water absorption, acid resistance, and chloride ion penetration. The results suggest that adding silica fume to recycled aggregates increases both the strength and durability of the concrete. The best results were achieved when 40% of the aggregates were replaced with building debris and 10% of the cement was replaced with silica fume. The results of this research indicate that the blended use of building debris and silica fume produces concrete that meets the required strength, durability, and sustainability criteria and is therefore an environmentally responsible approach to resource conservation and reducing construction industry waste.

1 Introduction

Concrete as a building material is among the most widely used construction materials worldwide, yet with its widespread use, there have been major environmental issues that have been raised due to its high consumption and the increase in construction and demolition (C&D) waste products [1]. Reusing C&D waste in the form of recycled concrete aggregate (RCA) has been recognized as an effective measure to reduce the disposal of such waste in landfills and conserve natural resources [2]. Empirical studies have suggested that concrete with RCA has the potential to achieve acceptable mechanical behavior, but its strength and

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durability generally follow an undesirable trend relative to normal concrete produced using natural aggregates [3]. The low performance of RCA concrete is mainly attributed to the existence of adhered aged mortar, which contributes to increasing porosity and decreasing interfacial transition zone (ITZ) [4]. These microstructural impairments affect the durability and extend the service life of recycled aggregate concrete (RAC). In order to resolve these limitations, A combination of additional cementitious materials (SCMs), most notably silica fume, has been widely studied [5]. Silica fume is characterized by minuscule particle size and a high degree of pozzolanic reactivity, and thus facilitates the densification of the cement matrix and refinement of the ITZ [6]. Experimental research has confirmed that silica fume significantly improves compressive strength, tensile strength and durability of RAC by reducing permeability as well as increasing resistance to chloride intrusion [7,8]. The use of densified silica fume in high-performance concrete that uses recycled aggregates has been cited to enhance significantly the qualities of durability, such as water absorption and hostile environment resistance [9]. Computer optimization and sophisticated statistical models, including the response surface methodology (RSM), have also been applied to evaluate the synergistic process of RCA, silica fume, as well as other SCM, including ground granulated blast furnace slag (GGBFS), on the mechanical and durability properties of concrete [10]. Further, techniques of surface treatment, such as the silica fume slurry treatment over recycles of coarse aggregates, have been seen to be promising in enhancing the bonding between aggregates and paste and improving the performance in strength [11]. The modern studies have also depicted that geopolymer concretes that include RCA and silica fume have better mechanical properties and strength than traditional cement-based systems and may thus be adopted as an environmentally sustainable alternative [12]. It is also proven that the synergistic usage of silica fume with fibrous substances increases the impact resistance, toughness, and longevity of RAC. Also, silica fume is effective in ultra-high-performance concrete (UHPC) with C&D waste, which leads to long-term performance and improved microstructural integrity. To conclude, the current literature clearly shows that silica fume integration is a key factor in reducing the limitations that come with recycled aggregates. RCA and silica fume have been used together to produce concrete of a sustainable nature with high strength and durability, hence marking strong potentiality of structural use in the rest assured, environmentally responsible construction practices.

2 Materials

The sustainable concrete that was studied in this study was intended to use building waste collected in recycling as a partial replacement of natural coarse aggregates (C&D). Concrete debris from demolished reinforced concrete buildings located within Coimbatore, Tamil Nadu, was used as the starting material for this study. The waste material included predominantly crushed concrete pieces with some remaining residual cement mortar still attached to the surfaces of the aggregates present in the waste. Debris was mechanically crushed and screened to produce aggregates with a nominal size of 10–20 mm, comparable to the sizes of conventional coarse aggregates used in concrete for structural applications. Contaminants found in the recycled materials, such as wood, metal, and brick fragments, were removed manually before reuse. The recycled aggregates had significantly greater absorption capacity than natural aggregates, as well as lower density due to the presence of adhered cement mortar and higher porosity of the recycled aggregates. The additional cementitious material was silica fume, an industrial by-product of silicon metal or ferrosilicon alloy, because its pozzolanic properties are well-documented and it improves the microstructure of the concrete and contributes to maximum strength and durability. The main binder used in all applications was ordinary Portland cement, and the natural fine aggregates were defined based on standards. Water and other necessary admixtures for the specified

workability were introduced according to the mix design. Table 1 presents the physical properties of the materials.

2.1 Physical Properties

Table 1. Physical properties of the materials

Material	Density (kg/m ³)	Water Absorption (%)	Specific Gravity	Particle Size / Description	Other Properties
Recycled Building Debris	2350	6	2.45	10 - 20 mm nominal size	Higher porosity, adhered mortar, variable strength
Natural Coarse Aggregate	2650	1.5	2.7	Well-graded crushed stone	High durability and strength
Silica Fume	2200	-	2.2	< 1-micron particles	High surface area ~15,000 m ² /kg, pozzolanic
Ordinary Portland Cement	3150	-	3.15	Fine powder	Blaine surface area 250-350 m ² /kg, sets in Hours
Natural Fine Aggregate	2,650	2	2.65	0.075 mm - 4.75 mm	Clean, well-graded
Water	1,000	-	1.0	Liquid	Free of impurities

3 Mix Design

Concrete mix of M25 grade meets the specifications outlined in IS 10262:2019. Concrete was designed by replacing the coarse aggregate with recycled building debris ranging from 20%, 40% and 60%, and replacing cement with silica fume ranging from 5%, 10%, and 15%. Such ratios are in accordance with IS 10262:2019 standard techniques and accounting of increasing water demand by porous debris. The water-cement ratio was kept within the permitted limits for structural concrete, and all mixtures were batched and mixed under the same conditions to minimize variation between mixtures. The water-cement ratio used in these mixes is 0.45. The workability was realised without the utilisation of the chemical admixtures through the regulation of the water-cement ratio and the aggregate gradation. The building debris recycled has been pre-dipped into a saturated surface dry (SSD) condition of the material to reduce the quick uptake of water and the loss of workability. The right mixing ratio of fine to coarse aggregates (1:1.75:2.75) was used to procure sufficient volume of paste to lubricate. All mixes were uniformly batched, the mixing time was controlled, and mixing procedures were similar to ensure homogeneous and workable concrete fit to be cast and compacted. All mixtures were made without chemical admixtures, but careful control of batching and mixing time ensured that they all had the same level of workability. The mix proportion was 1:1.75:2.75. The values representing the best mix concrete showed maximum mechanical and durability parameters such as water absorption, acid resistance, chloride

penetration at a debris content of 40%, and Silica Fume at a content of 10%.

4 Methodology

In making three cube samples (150 mm x 150 mm x 150 mm), a cylinder sample (150 mm x 300mm) for splitting, and a prism sample (100 mm x 100 mm x 500 mm) for bending. During all preparation and curing procedures, the cubes, cylinders, and prisms of each mix were submerged in water. In the construction, there were several concrete blends in which the natural coarse aggregates were partially substituted with recycled building waste in quantities of 20, 40, and 60 %t. On the same note, silica fume was used as a substitute for cement at 5, 10, as well as 15%. These replacement levels were employed as a tool to evaluate mechanical and durability performance with sustainable materials systematically at various levels. All the mixes were prepared by the same procedures of mixing, casting and curing as per the acceptable concrete testing procedures. The average of three test samples was used to calculate the reported mechanical and durability properties. There were acceptable differences observed in the sample-to-sample individual test results in the laboratory for the mechanical tests and durability tests for the concrete at the laboratory scale; however, there was no formal statistical analysis performed in this study. This creative approach provided the intended result consistent between mixes. Mechanical properties were tested for compressive strength, flexural strength, and split tensile strength in an effort to obtain proper mechanical performance at 7 days, 28 days, and 90 days curing times. Durability testing consisted of water absorption tests, which were performed in order to highlight porosity and permeability, acid resistance and chloride ion penetration resistance tests. Durability testing produces results in the form of how the sustainable concrete will behave in the environment over time when it is exposed to environmental aggressors. The outcomes of these experiments evaluated the effects of the recycled aggregate and silica fume on the concrete properties, but with particular attention on the optimum mix replacement material ratio to achieve sustainability goals and provide the corresponding level of structural performance. The line of approach in this study presents a chance to determine whether a new concrete mixture with C&D waste and silica fume is capable of substituting the traditional concrete construction system without sacrificing the utilization of the resources and causing waste products in the industry. The methodological approach also allows holistic evaluation of the process of enhancing silica fume with building recycled debris to offer sustainable concrete that is capable of fulfilling the requirements of mechanical and durability performance, as well as addressing sustainability goals and fostering sustainable construction industry practices. Future research may utilize larger data sets to conduct a more detailed statistical evaluation of the data collected.

5 Results and Discussion

5.1 Mechanical Properties

According to the research paper, replacing natural coarse aggregates with recycled construction waste has an impact on the mechanical properties of concrete. The study was able to show that 40% replacement of coarse aggregate produced a good balance between strength and sustainability. The increase in compressive, flexural and split tensile strength was noticed when a supplementary cementitious material was added to the concrete mix. Silica fume improved the microstructure of concrete by filling voids and developing additional calcium silicate hydrate as a byproduct of pozzolanic reactions that strengthen the concrete matrix. The highest performance of the mechanical properties was found at 40%

recycled aggregate, along with 10% silica fume replacement, representing the best value for meeting both structural and sustainable goals. Additionally, the densified characteristics of the silica fume provided an additional benefit of improving the durability properties of concrete. The durability testing for water absorption, acid resistance, and chloride ion penetration found that recycling debris provides similar durability characteristics as conventional concrete, however, it exhibited a much greater permeability and thus will have a higher degree of exposure to the ingress of chemicals. Silica fume allows for pore refinement through secondary calcium silicate hydrate formation that densifies the interfacial transition area between recycled aggregate and cement paste. Refining the pore structure helps to minimize the inherent weaknesses of the adhered mortar and increases load transfer performance. However, the use of silica fume has the capacity to decrease some of this performance degradation. These findings demonstrate that using a mixture of recycled C&D materials and silica fume is a practical method of producing new sustainable concrete products with acceptable mechanical properties and improved durability. The scientific society has made a huge step in promoting sustainable environmental practices through its efforts to reduce the reliance on natural aggregate and portland cement, both of which are costly, energy-consuming, and carbon-dioxide-emitting materials. Using recycled building materials also reduces the mass of construction waste accumulating in landfills and provides an alternative to disposing of construction debris. Therefore, the use of recycled building materials containing silica fume can be used to come up with quality, low-cost concrete mixes without affecting performance. This study indicates that sustainable construction using building debris can be realised in a cross-industry pilot scale to produce sustainable concrete in accordance with the circular economy and sustainable construction. A key takeaway is that, under appropriate quality control procedures and optimization of the concrete mix, the sustainable concrete applications demonstrate promise for sustainable concrete usage at scale in the structural applications industry.

Table 2. Compressive strength results

Mix ID (B+S)	Building Debris (B) (%)	Silica Fume (S) (%)	Compressive Strength (MPa)		
			7 Days	28 Days	90 Days
M1	0	0	20	31	36
M2	20	5	18.5	30.1	33.2
M3	20	10	20.3	32.7	36.5
M4	20	15	21	33.5	37.2
M5	40	5	17.8	29.6	32.8
M6	40	10	22.5	35.2	39.4
M7	40	15	22.8	35.7	40
M8	60	5	16	26.7	29.5
M9	60	10	17.5	28.9	32.3
M10	60	15	17.7	29.2	32.7

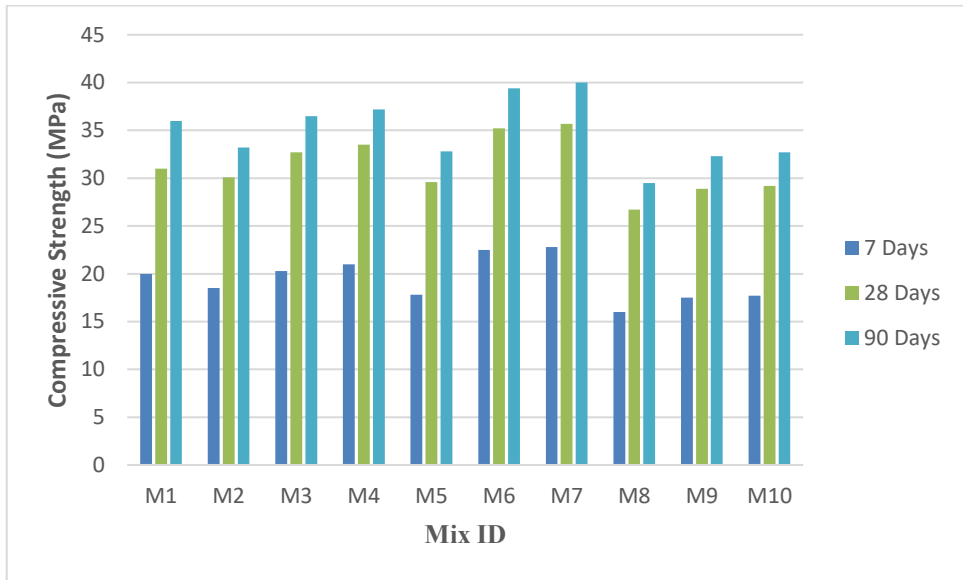


Fig. 1. Results of the compressive strength test with the replacement of building debris and silica fume

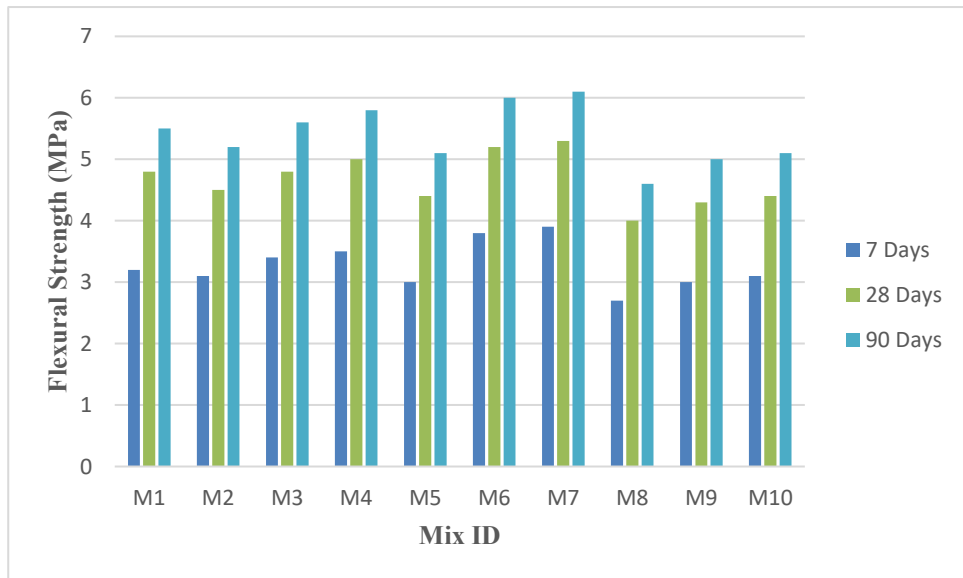


Fig. 2. Results of the flexural strength test with the replacement of building debris and silica fume

Table 3. Flexural Strength Results

Mix ID (B+S)	Building Debris (B) (%)	Silica Fume (S) (%)	Flexural Strength (MPa)		
			7 Days	28 Days	90 Days
M1	0	0	3.2	4.8	5.5
M2	20	5	3.1	4.5	5.2
M3	20	10	3.4	4.8	5.6
M4	20	15	3.5	5	5.8
M5	40	5	3	4.4	5.1
M6	40	10	3.8	5.2	6
M7	40	15	3.9	5.3	6.1

M8	60	5	2.7	4	4.6
M9	60	10	3	4.3	5
M10	60	15	3.1	4.4	5.1

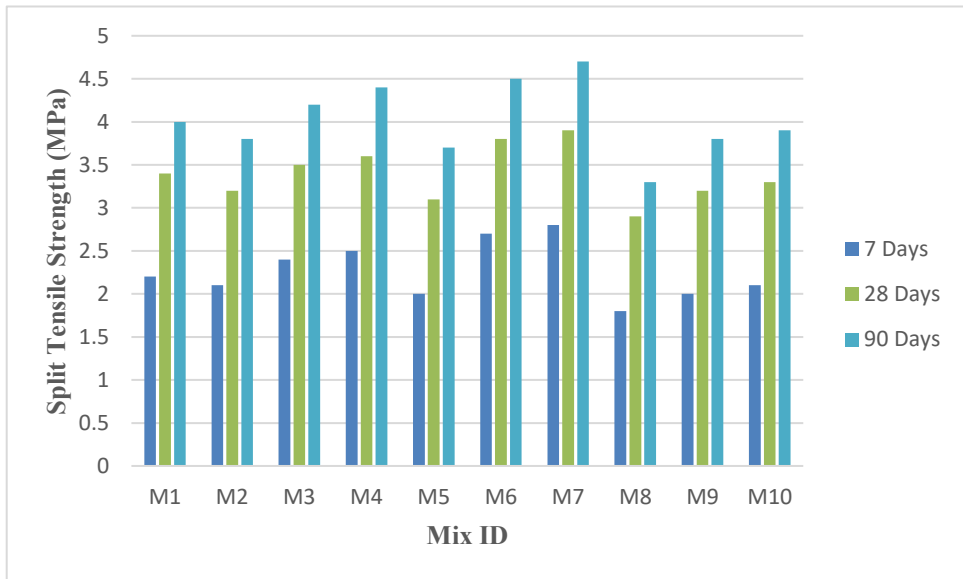


Fig. 3. Results of the split tensile strength with the replacement of building debris and silica fume

Table 4. Split tensile strength results

Mix ID (B+S)	Building Debris (B) (%)	Silica Fume (S) (%)	Split Tensile strength (MPa)		
			7 Days	28 Days	90 Days
M1	0	0	2.2	3.4	4
M2	20	5	2.1	3.2	3.8
M3	20	10	2.4	3.5	4.2
M4	20	15	2.5	3.6	4.4
M5	40	5	2	3.1	3.7
M6	40	10	2.7	3.8	4.5
M7	40	15	2.8	3.9	4.7
M8	60	5	1.8	2.9	3.3
M9	60	10	2	3.2	3.8
M10	60	15	2.1	3.3	3.9

5.2 Durability Properties

5.2.1 Water Absorption

The results associated with water absorption indicate that the addition of both silica fume and moderate contents of recycled debris has a great impact on the concrete durability in terms of porosity reduction and permeability reduction when compared to the 5.2% control mixture. Using 20% and 40% of debris mixed with silica fume led to a reduction in water absorption below that of the control sample. This is a sign of enhancement of microstructure and a decrease in pore volume.

The best combination of water absorption was 40/10 (40% of the debris and 10% of the

silica fume), which gave an absorption value of 3.7, which was the best overall combination of performance and sustainability. A debris content of 60% mix has a total water absorption of 6.1%, and with the addition of silica fume (4.30%), it is less than that without it. Therefore, combining moderate levels of debris with 10% silica fume is an excellent and sustainable way to achieve a durable concrete product. The water absorption was lower for concrete containing 40% mix of recycled concrete and 10% silica as opposed to the control sample with 5.2% water absorption. The water absorption dropped to 3.7%.

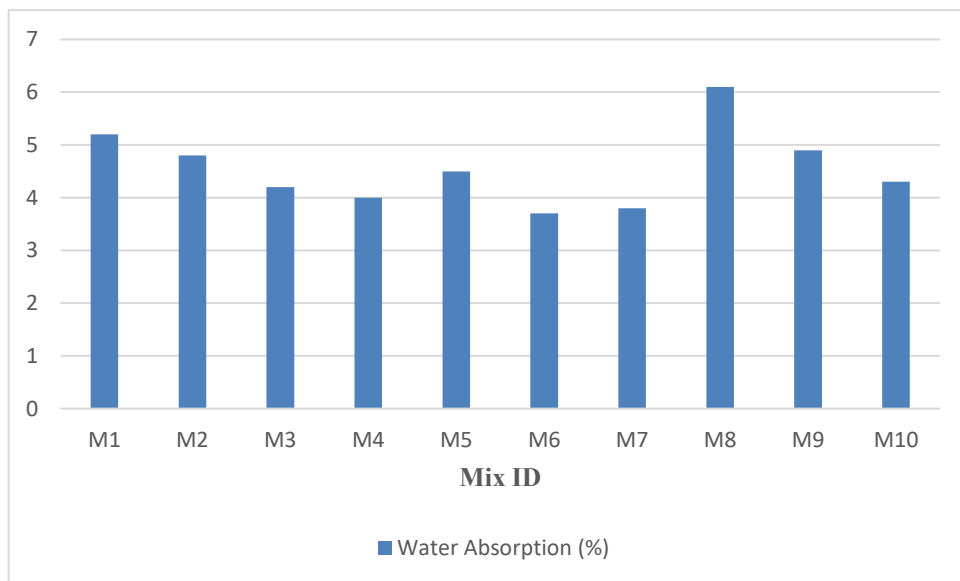


Fig. 4. Results of the water absorption test with the replacement of building debris and silica fume

Table 5. Water absorption results

Mix ID (B+S)	Building Debris (B) (%)	Silica Fume (S) (%)	Water Absorption (%)
M1	0	0	5.2
M2	20	5	4.8
M3	20	10	4.2
M4	20	15	4.0
M5	40	5	4.5
M6	40	10	3.7
M7	40	15	3.8
M8	60	5	6.1
M9	60	10	4.9
M10	60	15	4.3

5.2.2 Loss due to acid attack

Within the control mix, 2.8% of weight loss and 25.0% strength reduction occurred when in contact with sulphate compounds, which represents typical results for ordinary Portland cement concrete. The addition of SF progressively reduced deterioration for all levels of RBD due to the pozzolanic reaction of SF, creating secondary C-S-H gel, which densifies and refines the pore structure of the interfacial transition zone between the two materials. At the RBD of 20%, SF dosages of between 5 and 15% were found to have a 10% to 34% reduction

in the strength loss compared to control, in which the 15% SF provided the greatest strength retention value.

The same patterns were observed for RBD 45%, where the RBD 40 and SF10 mix was optimally performing, with a further increase of 52% in strength retention compared to the control, due to effective blockage of pore space and no excessive loss of workability. At a 60% relative batch dryness, the increase in losses is due to increased micro-cracking and porosity in the recycled aggregate, which provide entry points for acid to penetrate the recycled aggregate particle. Although SF did partially compensate, it also exhibited the threshold effect; the inherent weakness of the aggregate is dominant above the RBD of 40%. The study demonstrates that using a combination of SF and 40% RBD will maximize the acid resistance performance of the combination, thereby making it possible to use this type of concrete as a "green" alternative for sewage infrastructure.

Table 6. Losses due to acid attack (H₂SO₄)

Mix ID (B+S)	Building Debris (B) (%)	Silica Fume (S) (%)	Weight Loss in H ₂ SO ₄ (%)	Strength Loss in H ₂ SO ₄ (%)
M1	0	0	2.8	25.0
M2	20	5	2.4	22.5
M3	20	10	2.1	18.0
M4	20	15	2	16.5
M5	40	5	2.3	20.0
M6	40	10	1.8	12.0
M7	40	15	1.9	13.5
M8	60	5	3.2	32.0
M9	60	10	2.5	24.0
M10	60	15	2.2	19.0

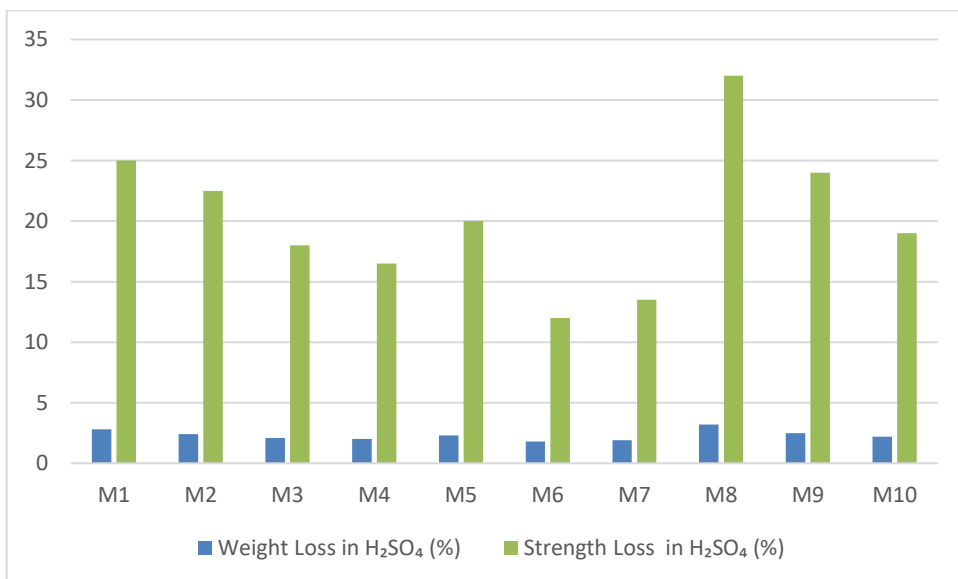


Fig. 5. Results of weight and strength loss due to acid attack with replacement of building debris and silica fume

5.2.3 RCPT Test

The Rapid Chloride Permeability Test (ASTM C1202) is a durability test that measures the charge in coulombs that passes through a concrete sample prepared as 50 mm slices after 28 days of curing to assess permeability risk. The addition of the debris would also reduce the permeability to chloride ions; the chloride permeability of the control concrete was determined to be 4200 coulombs, whereas, for the concrete containing 40% recycled concrete and 10% silica fume, it was determined to be 2100 coulombs, resulting in a reduction of about 50%. It has been improved through the replacement of Portland cement with silica fume, improving pore refinement and densification of the Inter- Transition layer around often recycled concrete particles, lowering the RCPT classification from "High" to "Very Low" and demonstrating suitability for marine or de-ice environment applications, and also promoting sustainable construction practices.

Table 7. RCPT results

Mix ID (B+S)	Building Debris (B) (%)	Silica Fume (S) (%)	RCPT (Coulombs)	Chloride Permeability
M1	0	0	4200	High
M2	40	10	2100	Very Low

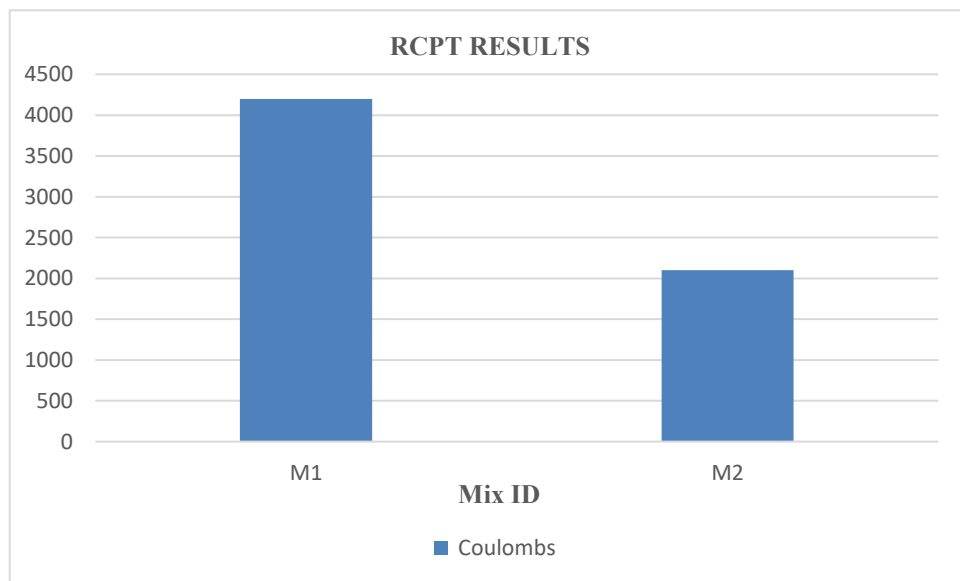


Fig. 6. Results of RCPT with replacement % of building debris and silica fume

6 Conclusion

This study reveals that recycled building debris can be used effectively to replace a high percentage of between 25-50 percent of natural coarse aggregate in a concrete mixture, and that the addition of silica fume as an additional cementitious material can improve the mechanical and durability properties of concrete mixes using recycled building debris significantly. Particularly, the optimum performance is when the concrete contains 40% recycled debris aggregates, and the cement is replaced with 10% silica fume. Improved compressive, flexural, and split tensile strengths were observed across all curing time points.

Furthermore, the enhanced durability of the concrete, indicated by reduced water absorption, greater acid resistance, and reduced chloride-ion penetration, was significantly improved not only by the pozzolanic effects of recycled-debris aggregates and silica fume, but also by microstructural densification. The use of recycled C&D waste in conjunction with silica fume-type material for cement replacement not only provides solutions for environmental issues related to construction and demolition practices by reducing natural resources and consumption, as well as reducing construction waste, but it also allows for appropriate structural and durability performance, as determined in the present research for applicable use. Thus, the present research provides evidence that sustainable, efficient concrete is possible, promoting resource conservation, reduced material waste, improved infrastructure resilience for long-term use, and potential to help promote more eco-friendly practices in the construction industry.

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