[BAU Journal - Science and Technology](https://digitalcommons.bau.edu.lb/stjournal)

Volume 3 | Issue 2
ISSN: 2706-784X

Article 3

June 2022

PRODUCTION OF LOW-COST SELF-CONSOLIDATING CONCRETE (SCC) USING MANUFACTURED AGGREGATES

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Recommended Citation

Raydan, Rabab; Chamseddine, Farah; Jahami, Ali; Baalbaki, Oussama; Khatib, Jamal; and Elkordi, Adel (2022) "PRODUCTION OF LOW-COST SELF-CONSOLIDATING CONCRETE (SCC) USING MANUFACTURED AGGREGATES," *BAU Journal - Science and Technology*: Vol. 3: Iss. 2, Article 3.
DOI: https://www.doi.org/10.54729/HKRO9755
Available at: https://digitalcommons.bau.edu.lb/stjournal/vol3/iss2/3

1. INTRODUCTION

After water, concrete is the most frequently utilized substance on the planet. Concrete production needs a large quantity of virgin resources. The concrete technology is always in improvement. Sustainable development and a clean environment are critical components of the circular economy all over the world (Khatib *et al.*, 2019[a], Khatib *et al.*, 2019[b], Jahami *et al.*, 2019, Khatib *et al.*, 2020, Khatib *et al.*, 2021). It is a necessity to maintain a healthy built environment preventing environmental degradation.

Nowadays the urge for high performance concrete with good workability is widely requested (Raj, 2021). Thus, Self-Consolidating Concrete (SCC) is a choice that has the ability of self-consolidating into a mold without any external vibration needed. It is chosen since this type of concrete has low yield stress, good segregation resistance, high deformability, and moderate viscosity that never needs to be consolidated to fill forms or flow (Ramkumar *et al*.,2020). SCC can flow into very tight forms or sections with congested reinforcement and leave no voids; however, it gains its fluid properties from an unusually high proportion of fine aggregate, such as sand (typically 50%), combined with superplasticizers (Raj, 2021). In the diagram below, the constituents of conventional concrete and self-compacting concrete are compared.

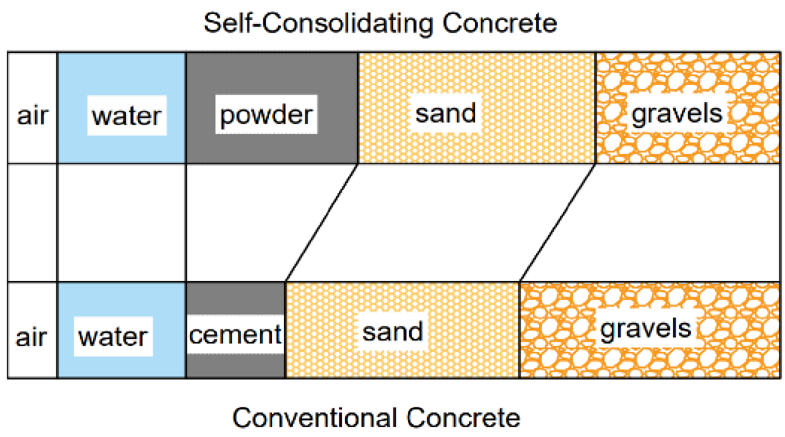

Fig.1: Components of Self-Consolidating Concrete Compared to Conventional Concrete

The Self-Consolidating Concrete (SCC) in concept was introduced in 1986 by Prof. Okamura at Ouchi University, Japan, when a skilled labor was in limited supply, causing difficulties in concrete-related industries (Khanala *et al.*, 2021). A committee was formed to study the properties of self-Consolidating concrete and investigate its workability. The first trial of self-Consolidating concrete was done in 1988 and named as “High Performance Concrete”, which was later proposed as “Self-Consolidating High-Performance Concrete” (Al_jubory *et al.*, 2020). The first generation of SCC used in North America was characterized using high content of binder and chemicals admixtures, usually superplasticizer to improve flowability and stability (Khanala *et al.*, 2021). Yet, SCC has many major benefits which include improved construction methods, durability and strength, ease of placement without the need of vibration or mechanical consolidation, and acceleration in the project schedules with reduced skilled labor (Qabaja, 2019).

It is obvious that availability of sand for concrete production becomes a problematic issue in Lebanon due to the difficulty to find a natural sand that fulfill the standards requirements in terms of suitable grading, low fines, and clay contents. Issues related to aggregates prices and technical issues of the production are usually among the topics of concern to aggregate producers. It is to be noted that up to 30 percent (rock dependent) of the material acquired from the bedrock is reduced to sizes smaller than 4 mm and thus cannot be used as coarse aggregates. Also, it is critical to investigate the processing and reactivity of supplementary cementitious materials (SCMs) such as Silica Fume in concrete, as well as their impact on cement hydration and strength development (Smirnova *et al.*, 2020).

The use of alternative aggregates helps the concrete industry save natural resources by minimizing the need of natural aggregates (Sasanipour *et al.*,2019). Manufactured sand can be one option which is made by crushing a cubical granite stone with grounded edges, washed, and well graded to be used as a construction material for substitution of natural sand (Mahalakshmi *et. al*, 2020). Yet, using this type alone has a detrimental effect on concrete characteristics. Superplasticizers are concrete admixtures that are used to lower the water content of a mix while maintaining the flowing properties of a mix (Mansoor *et al.*, 2018).

The addition of Silica Fume as a cementitious material additive can aid in improving the concrete's quality. Replacing Portland cement with Silica Fume can contribute to energy reservations and pollution reduction (Sasanipour *et al.* 2019, Mahalakshmi *et. al* 2020). As Mahalakshmi et al. (2020) stated, that using Silica Fume in High Strength Self Consolidating Concrete tends to be remarkably effective reducing adverse effects that occur due the need of having high cement content and fines to avoid having segregation and workability problems in addition to improving the concrete's rheological and mechanical properties (Mahalakshmi *et. al*, 2020). Silica fumes have recently obtained popularity as a partial substitution for cement in the construction of sustainable buildings. Micro silica, also referred as Silica Fume, is an accumulation of soot that flees with exhaust gas during the melting of industrial silicon and ferrosilicon at elevated temperatures. High-reactivity SF can react with calcium hydroxide ($Ca(OH)_2$) to generate calcium silicate hydrate (C-S-H) and fill surface pores and voids between aggregate particles, increasing the structure's compactness and compressive strength (Guo *et al.*, 2020).

Silica fume and superplasticizer are complementary elements used to generate self-leveling concrete. One of the most appealing aspects of adopting Silica Fume in SCC is its small size, which allows for self-compaction (Ofuyatan *et al*., 2021). In the area of flow-ability, the use of Silica Fume as a partial cement substitute resulted in a noticeable improvement over the fresh state properties of the concrete. This demonstrates its suitability for use as a substitute for cement in the construction sector. On the basis of mechanical properties, it is proven that higher partial replacement resulted in lower compressive strength due to a weak interfacial transition zone (Ofuyatan *et al*., 2021).

Furthermore, overcoming the durability difficulties of SCC including RCAs by incorporating Silica Fume increases the lifespan of buildings, resulting in economic advantages. Currently, the construction design guidelines allow for the selection of the concrete constituents based on a feasibility analysis and the need to have an economical approach. However, the regulation paperwork should include an assessment of concrete's comparative environmental effect (Smirnova *et al.*, 2021).

This work aims to perform several concrete trial mixes that embody the utilization of manufactured aggregates ratio and percentages of Coarse Aggregates and Manufactured Sand to Natural Sand in addition to inclusion of Silica Fume in creating high strength self-consolidating concrete. Six concrete mixes were considered for this purpose. The rheological and mechanical properties such as J-Ring, T500, Slump Flow, Visual Stability Index and Compressive Strength tests were determined for each concrete mix and compared to choose the most adequate mixture. In addition, the mixtures were compared in economic perspective to meet a cost-effective choice of mixture.

2. METHODOLOGY

2.1 Vertical Shaft Impact (VSI)

The Vertical shaft impact (VSI) technology is one of the most used machines in the construction industry. Using impact crushers as an alternative to the conventional crushing systems is favored for its high capacity of producing substantial number of fines with reduced particle size of stones and ores. It is known for its mechanism that is characterized by its cost-effectiveness; In VSI impact crushers, the materials are crushed by aid of an impact load which generates high kinetic energy driving the materials to hit a sharp-edged rigid object and result in class sizes crushed aggregates. Impact load crushing causes the chunks of materials on the strips to create tension peaks that spread at different speeds. Having fines with all class sizes to generate more isometric and tough end products. Using such aggregates is desirable in concrete applications as it exhibits an improvement in the material's rheological properties (Al-Khasawneh, 2021).

DOI: https://www.doi.org/10.54729/HKRO9755

2.2 Mix Design

The Self-Consolidating Concrete (SCC) mix design is prepared on the basis of using Silica Fume (SF) as a supplementary cementitious material, round aggregates and manufactured fine aggregates as a replacement of natural fine aggregates several trials to estimate the optimal rheological and mechanical performances. Superplasticizer (ViscoCrete 5930) third-generation superplasticizer satisfying the ASTM C494-05 Types G and F standards has been used with specific gravity of 1.07 kg/m^3. Portland Cement (PC 42.5) Type I Portland cement meeting ASTM C150-95 was used with a specific gravity of 3.15 kg/m^3 in addition to SCMs inclusion of Silica fume with specific gravity of 2.19 kg/m^3. During each trial, the aggregate(s) shall constitute a minimum of 60% of the total mass of concrete mixtures meeting aggregate requirements described in ASTM C33-16 and the contribution of coarse aggregates with a minimum size of 5 mm and maximum size of 9.5 mm must be at least 30% of the total aggregates mass. The properties of the aggregates used in the trial mixes are listed below.

2.2.1 Processed Coarse Aggregates

Coarse aggregates produced by Vertical Shaft Impact Technology (VSI) were presented as an innovative technology that intends to tackle the challenges of obtaining aggregates with proper grading, particle shape close to natural round aggregate with low fines and clay contents as shown in figure 2. The aggregates used in this investigation were rounded with a 9.5 mm as maximum particle size, an oven dry bulk specific gravity of 2.64, absorption of 2.6, and a water content of 1.29%. Furthermore, the aggregates used in the concrete mixes were graded, as shown in the figure 4.

Fig.2: Manufactured Round Aggregates

Fig. 3: Natural Aggregates

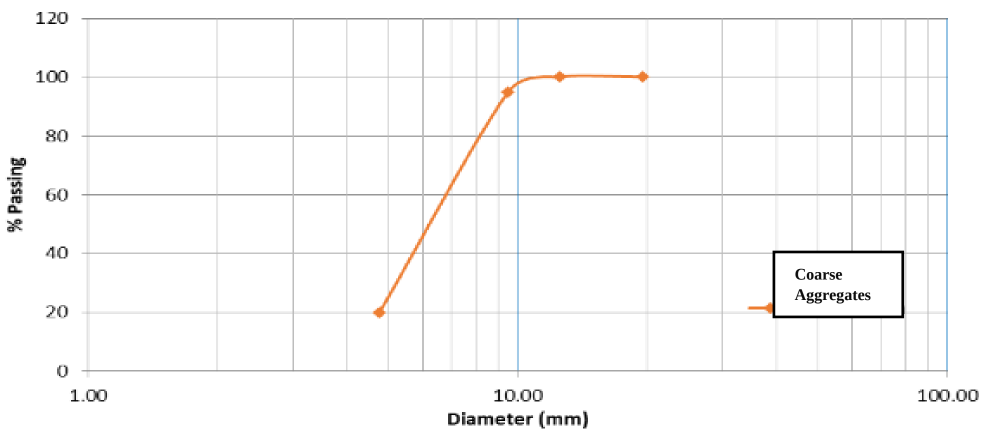

Fig.4: Sieve Analysis for the Coarse Aggregates

2.2.2 Manufactured Washed Sand

Manufactured fine aggregates often surpass natural sand. Simultaneously, the challenges in generating economical mixes with adequate workability (fresh state characteristics of concrete) are commonly cited as the primary issue that might cause the use of manufactured sand unfavorable in many cases.

The VSI technology demonstrated an improvement in the properties of concrete. The improvements proved the introduction of measurable changes in the fresh concrete properties. The round shape helps in providing enhance mobility of concrete with lower demand of High range water reducing admixtures.

To lower the overall fines content, the current state-of-art for crushed sand production is Vertical Shaft Impact Technology (VSI) shaping and wet or dry classification. The resulting products can be successfully used as high-quality manufactured sand. It has a bulk specific gravity (oven dry) of 2.61, absorption of 2.23, and a moisture content of 0.2 %. Furthermore, the aggregates used in the concrete mixes were graded and exhibited almost the same grading as the natural sand used, as shown in figure 5.

2.2.3 Natural Sand

Well-shaped (rounded) natural sand decreases the percentage of voids in the concrete microstructure and lowers the paste content while increasing the mixture's workability. The one used in this investigation has an oven dry bulk specific gravity of 2.42, absorption of 1.45, and a moisture content of 0.2%. Furthermore, the aggregates used in the concrete mixes were graded, as shown in the figure 5 below:

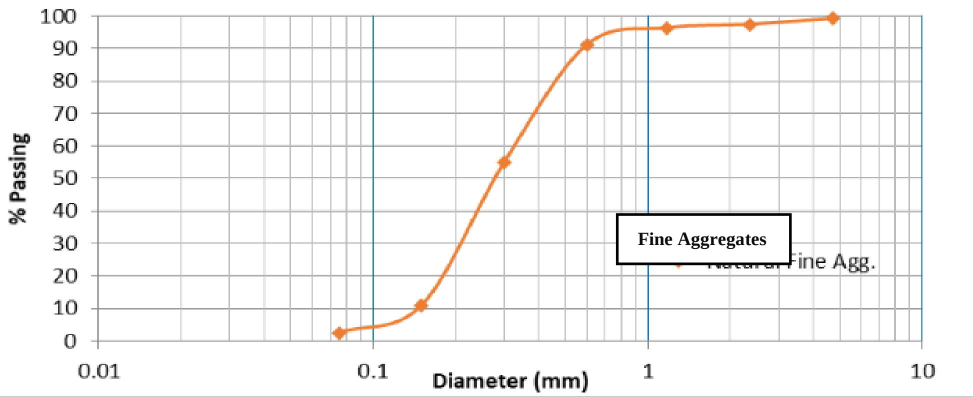

Fig.5: Sieve Analysis for the Fine Aggregates

Six trial mixes are prepared on the basis of seeking the optimal percentages of materials to satisfy the SCC workability requirements while maintaining high strength performance. These trials were conducted and examined to determine the ideal mechanical and physical performances of SCC with Silica Fume (SF), round and manufactured aggregates as a replacement for natural aggregates. These trials were conducted on a one m^3 volume. During each trial, the aggregate(s) must account for at least 60% of the total mass of concrete mixes fulfilling (ASTM-C33) criteria. The mix proportions are shown in Table 1.

Table 1: Experimental Mix Designs

Material	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
OPC Type 1 (kg)	500	504	504	504	525	525
Water (kg)	144.2	166.2	166.6	166.4	138.3	165.1
MWS (kg)	853.3	603	575	603	729.3	668
MCA (kg)	704	757	757	742	742	742
NS (kg)	187	297	323	297	270	247
Micro-silica (kg)	50	56	56	56	45	45
SP admix (Liter)	12.5	12.6	12.6	12.6	13.1	14.3
W/C	0.26	0.3	0.3	0.3	0.24	0.29
% FA	60%	54%	54%	55%	57%	55%
% NS from FA	18%	33%	36%	33%	27%	27%
% MWS from FA	82%	67%	64%	67%	73%	73%

(NS: Natural Sand, FA: Fine Aggregates, MWS: Manufactured Washed Sand, OPC: Ordinary Portland Cement, SP: Superplasticizer)

2.3 Mixtures Preparations

2.4.1 Batching

The concrete batching has been done per m^3 of concrete as shown in Fig. 7. The coarse and fine aggregates are mixed together for approximately 2 minutes (after sieving them using the mechanical shaker). The cement and silica fume are added together while continuing mixing. 70% of the mixing water (mixed with superplasticizer) were gradually added. Finally, the remaining water was added, and the mixing was continued to obtain a freshly mixed concrete.

Fig.6: Mix Design Materials Batching

2.4.2 Casting and Curing

From each trial mix, a total of 6 cubical concrete specimens of (100 mm x100 mm) dimensions are prepared for determining the compressive strength after 7 days of moist curing. The molds are lubricated properly for easy demolding and then filled with self-Consolidating concrete without compaction. The specimens are demolded after 24 hours and then cured at the laboratory conditions for 7 days. The casting process of cubes for the specimens are shown in Fig. 8 below.

(a) (b)

Fig.7: Casting and Curing

2.4 Testing

The tests made to assess the properties of the self-consolidating concrete included: Slump Flow, J-Ring, Visual Stability Index (VSI), T_{500} and Compressive Strength tests were conducted as shown in Fig.9 and Fig.10 respectively below.

Slump-flow testing is adopted test method to assess the flow ability of self-consolidating concrete (ASTM C1611-09b). A standard slump cone (200mm by 100mm by 300mm) is filled with concrete without any tamping, lifted, and measured in terms of mean spread diameter. As reported by the ACI Committee 237 *(*450 to 760 mm) diameter of spread is adequate for SCC. The higher the slump flow value, the greater ability to fill formwork under its self-weight.

Visual Stability Index (ASTM C-1611) is implemented to determine the segregation stability of the mixture. It is determined through visually rating the stability of the slump flow patty where a mixture is considered stable with a VSI rating of 0 or 1 where no segregation potential is present.

The T_{500} test aims to quantify the flowing ability of self-consolidating concrete with a relative index viscosity index through measuring the time needed for the slump flow to reach a diameter of (50 cm) The shorter the time, the lower the viscosity of the mixture is. As per the ACI Committee 237, it is stated that the mixture's T50 time of 2 seconds or less indicates a low viscosity and adequate spread concrete mixture. The J-Ring test is an indicator of the passing ability of self-consolidating concrete. It is assessed through the ability of slump flow to pass between the re-bars and is using rebars spaced kept three times of the maximum size of the coarse aggregate for normal placement of reinforcement consideration. The mixture's passing ability is assessed according to (ASTM C-1621).

The compressive strength assesses the mechanical properties of the self-consolidating concrete according to cubical specimens that are cast, and water cured for 7 days.

(a) (b) (c) (d)

Fig.8: Slump Flow, Visual Stability Index (VSI), J-Ring, and T_{500} Tests

(a) (b) (c)

Fig.9: Compressive Strength Test

3. RESULTS AND DISCUSSION

3.1 Rheological Properties

From the results below, it can be noticed that the blend of round aggregates and manufactured sand in SCC improves the workability, reduces segregation, and enhances the filling ability when compared to normal mix of SCC. The systematic experimental approach showed that the use of round aggregates resulting from Vertical Shaft Impact Technology (VSI) in conjunction with the replacement of natural fine aggregate with manufactured fine aggregates (about 73%) and using around 2.7% of Polycarboxylate superplasticizer around 8% Silica Fume (SF) from total cementitious materials could produce high strength self-Consolidating concrete without segregation potential. The optimal mix was determined based on both the characteristics of the concrete and the overall cost of the mix. Despite the fact that mix 1 had the lowest cost, the flow is inefficient. As a result, the logic suggests selecting the second most cost-effective option; mix 6, which also performed well in terms of flowability, thus we may consider it to be the optimal one. Ahlawat et al. (2015) offered an SCC mix design in which the fine and coarse aggregate content were adjusted so that the fine

DOI: https://www.doi.org/10.54729/HKRO9755

aggregate accounted for about (50- 60) % of the total aggregate with or without a viscosity modifying agent. Additionally, three synthetic PC-based superplasticizers were produced utilizing radical polymerization techniques, according to Felekoglu et al. (2007). A mixture with 2.3 wt% P3 type SP produces superior results.

The results showed that silica fume could be used successfully in producing self-Consolidating high-strength concrete MPa with reduced segregation potential. The Visual Stability Index (VSI) assessment indicates that upon increasing the percentage of Manufactured Washed Sand in the mix from the total fine proportion improves the segregation resistance and densifies the mixture attaining an adequate balance between concrete flow and stability which is expressed in the slump flow results in Fig.11 and Visual Stability Index (VSI) Assessment in Table 2. The flow thereby is assessed through the T_{500} test which attained a range of flow duration as shown in Fig. 12 between 3-5 seconds which is within the desired expectations for SCC mixtures.

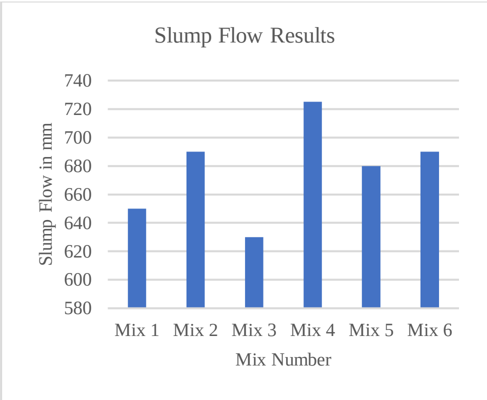

Fig.10: Slump Flow Results

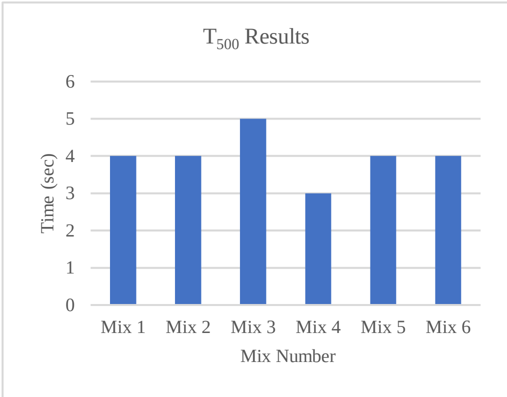

Fig.11: T_{500} Results

Table 2: Visual Stability Index (VSI) Assessment

Mix	Visual Stability Index (VSI) Index	Stability	Comments
Mix 1	3	Highly Unstable	Sticky, High Segregation
Mix 2	2	Unstable	Slight Segregation
Mix 3	3	Highly Unstable	High Bleeding
Mix 4	1	Stable	No Segregation nor Bleeding
Mix 5	0	Highly Stable	No Segregation nor Bleeding
Mix 6	0	Highly Stable	No Segregation nor Bleeding

3.2 Compressive Strength

The compressive strength test is done in accordance with (ASTM-C39) for determining the compressive strength after 7 days of moist curing. Three (10 cm x 10 cm x10 cm) cubes were cast from each mix to determine the mechanical properties of the SCC. The results in Fig. 14 show a trend that exhibits outcomes ranging between 50 MPa and 62 MPa at max. This high strength relies on the dense microstructure of the concrete that is obtained through the well graded aggregate blend and the addition of Silica Fume which works on improving the concrete strength at early age. Shanmugapriya and Uma (2013) conducted an experimental study on silica fume as a partial replacement for cement. The analysis indicated that the optimum dose of silica fume was discovered to be 7.5 % (by weight) when used as a partial replacement of conventional Portland cement, which was consistent with our findings.

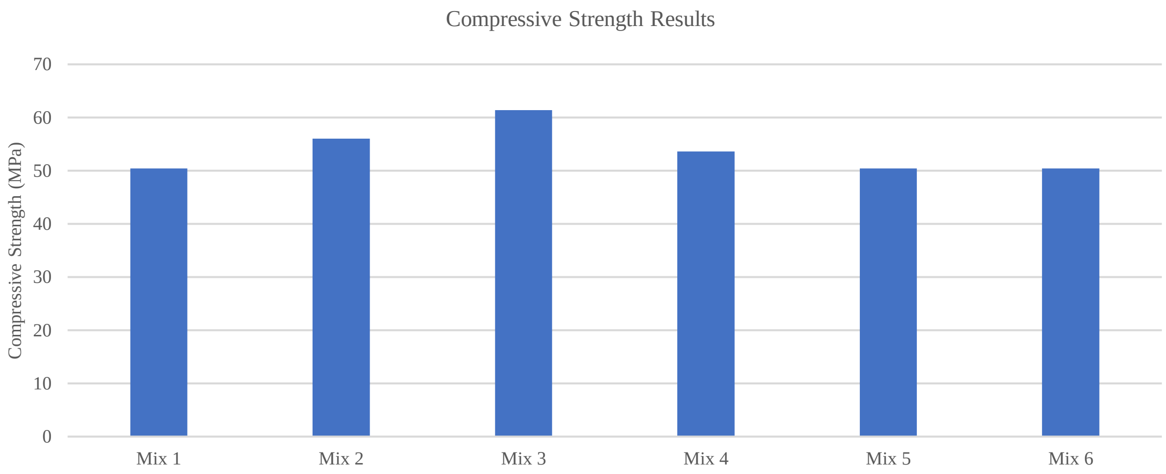

Fig.12: Compressive Strength Results

3.3 Cost Analysis

By using self-consolidating concrete, the cost of the initial materials might be 10% to 15% higher but with a good return. The elimination of vibrator operators and reduction of the number of skilled labors can compensate the extra cost. SCC can also speed up the construction process, from production, to placement, to the quality of the final concrete offsetting the initial cost. In this study, the use of manufactured aggregates plays a huge role in reducing the cost since they are priced lower than natural aggregates and are easier to transport and process. After assessing the cost/batch mixtures, the cost tends to show a reduction when utilizing manufactured aggregates in the mixtures when compared to the mixtures including individual use of natural aggregates. With illustrated comparison among the mixtures satisfying the required SCC properties and cost effectiveness in Fig. 13, it can be concluded that Mix 6 in Table 3 below which uses 73% of the total FA as MWS aids in reducing the cost sharply as calculated. The cost, quality, and time are key factors which prove significance in construction were improving any without negatively affecting other factors places interest of civil engineering.

Table 3: Cost/kg of Materials Used

Material	Unit cost	Cost/kg
PC Type 1	100$/ton	0.1
Water	-	-
MWS	15$/ton	0.015
MCA	12$/ton	0.012
NS	30$/ton	0.03
Silica Fume	275$/1 kg	0.4
SP admix	0.5$/L	0.5
Total	---	1.057

DOI: https://www.doi.org/10.54729/HKRO9755

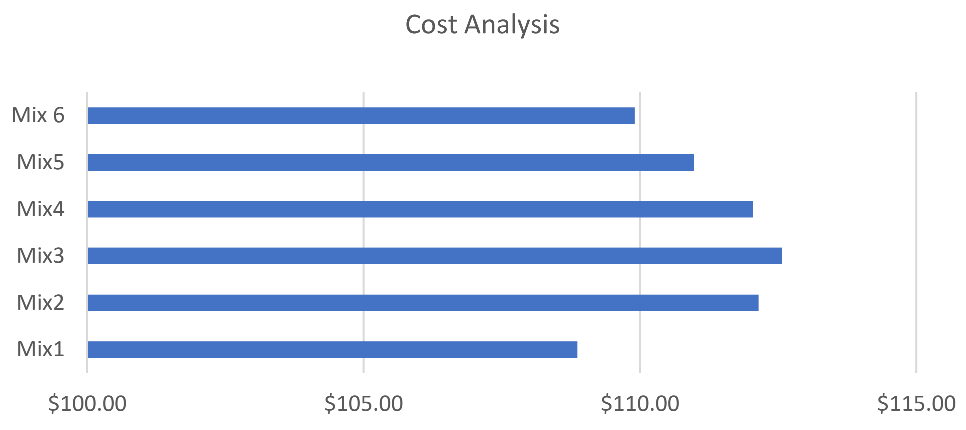

Fig.13: Cost Analysis Results

4. CONCLUSIONS

An overview of the development, properties, and advantages and disadvantages of using self-consolidating concrete has been outlined. Further, based on experimental study on the development of high-strength, economical, self-consolidating concrete incorporating Silica Fume and manufactured aggregates, the following general conclusions can be drawn:

1. The manufactured rounded aggregates of percentages 73% from total fine aggregates proportion, 2.7% of Polycarboxylate superplasticizer and around 8% Silica Fume (SF) from total cementitious materials can succeed in reaching high strength concrete with optimum workability and mechanical properties help in maintaining the mobility, attaining high workability of concrete with a noticeable improvement when compared with natural aggregates.
2. Silica Fume combined with rounded aggregates tends to improve the concrete early strength and contribute to the workability enhancement without affecting the flow and or implementing a segregation potential
3. Manufactured aggregates in the mix outperform natural sand through aiding in a well graded mix of aggregates which densifies the microstructure and in return improves the compressive strength.
4. The use of manufactured aggregates has a huge role in reducing the overall concrete cost due to the ease of transport and process in addition to being a sustainable solution that contributes to the reduction of wasting natural resources and work on making use from the available.

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