Production of Self Compacting Concrete using Recycled Brick Aggregate

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PROJECT APPROVAL

This is to certify that the thesis entitled "**Production of Self Compacting Concrete using Recycled Brick Aggregate**" submitted by Muhtadee Ur Rahman Chowdhury, Abu Rafe Faiyaz and Arian Asib has been approved as partial fulfilment of the requirement for the Degree Bachelor of Science in Civil Engineering at the Islamic University of Technology (IUT).

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DECLARATION

We declare that the undergraduate research work described in this thesis was completed by us under the expert supervision of Professor Dr. Md. Tarek Uddin. The appropriate cautionary measures have been taken to guarantee that the work being done is unique. The material presented here has not been copied, plagiarized or placed elsewhere for any reason other than publication.

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DEDICATION

To our parents, whose unwavering support, boundless patience, and countless sacrifices have shaped us into who we are today. Your endless encouragement and belief in us have been our greatest inspiration, allowing us to pursue our ambitions and achieve our goals. We owe you our deepest gratitude and dedicate this work to you with all our love.

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Abstract

Sustainability is a pressing concern in construction, especially with dwindling material resources. Bricks are frequently used in construction works in Bangladesh as coarse aggregate, and recycling of this concrete after demolition of buildings provides a sustainable solution. This study investigates the fresh and hardened properties of self-compacting concrete (SCC) incorporating recycled brick aggregate (RBA) as coarse aggregate as well as fine aggregate. To understand the possibility and challenges for making SCC using RBA, ten different mixes were designed using RBA of maximum size of aggregate as 15 mm and 20 mm. Natural-river sand and recycled fine aggregate were used as fine aggregate. As binder CEM Type I and blended cement with fly ash, slag, and silica fume were used. The water-cement ratio and sand-to-aggregate ratio were 0.35 and 0.50 respectively; while admixture dosage was adjusted based on the flow ability of concrete. A total of 150 cylindrical specimens were casted. Compressive strength tests were conducted at 7, 14, 28, and 90 days respectively. The obtained results demonstrated that RBA can be utilized to make SCC that satisfies both fresh and hardened properties when combined with either natural or recycled brick aggregate as fine aggregate. Notably, partial replacement of cement with fly ash and slag only, significantly improved fresh properties, while on the other hand, adding silica fume improved resistance to segregation, in certain situations, this came at the expense of decreased flow characteristics. The flow diameters were within the range of 500 - 700 mm and for certain cases V-funnel test results were varied from 6-12 seconds. Cases with recycled sand as fine aggregate showed a tendency of less flow ability compared to the cases made with natural sand cases. On the other hand, the cases with natural sand and fly ash and slag as partial replacement of cement yielded minimal strength in comparison to the cases made with recycled brick aggregate as fine aggregate. The compressive strength is increased significantly when silica fume was added. By using RBA as coarse aggregate and fine aggregate and adding silica fume, it is possible to make SCC of compressive strength 42 MPa.

Keywords:

Recycled Brick Aggregate; Sustainability; Self Compacting Concrete.

Chapter 1: Introduction

1.1 General

Concrete consumption in the world is estimated at two and a half tons per capita per year (equivalent to 17.5 billion tons for seven billion population in the world). An approximate of 2.62 billion tons of cement, 13.12 billion tons of aggregate, and 1.75 billion tons of water are needed to make this enormous amount of concrete. A significant amount of natural resources can be saved if materials are recycled for new constructions. (Mohammed et al., 2015) Bricks are one of the most commonly used construction materials. By reusing bricks from demolished structures, we can extend the lifespan of the existing resources as well as being a more sustainable option. The higher water absorption and porous structure of Recycled Brick Aggregate (RBA) are the main challenges for the application of RBA in Self Compacting Concrete (SCC) that requires high fluidity and good mechanical strength. The incorporation of RBA decreases the flowability and passing ability of SCC. (Tang et al., 2020) Self - Compacting Concrete (SCC) prepared with recycled aggregate has not been extensively studied yet. In particular, in the last few years some researches have been made using Construction and demolition waste in SCC, particularly with coarse recycled concrete aggregates. (Manzi et al., 2017)

1.2 Background

Self-compacting concrete (SCC), also known as self-consolidating concrete, is a modern concrete technology gaining popularity in the construction industry, offering superior flowability and self-consolidation properties without the need for external energy input. (Malherbe, 2015). Originating in Japan in 1988, SCC was developed to enhance construction quality and address the declining availability of skilled workers. While SCC is not expected to entirely replace conventionally vibrated concrete, its usage in both precast and ready-mix markets is projected to increase globally due to advancements in technology, client demand for higher-quality products, and challenges in accessing skilled labour. (Okamura & Ouchi, 2003)

The property that makes Self-Compacting Concrete (SCC) unique is its ability to flow without segregation into formwork and around intricate reinforcing arrangements. Filling capacity, passage ability, and segregation resistance are important engineering characteristics of fresh SCC that are mainly determined by rheological characteristics and geometric limitations. SCC's fluidity affects air-void stability and formwork pressure until thixotropic stiffening or hydration occurs. (Geiker & Jacobsen, 2019)

While SCC offers several advantages, it also poses certain challenges in terms of production, placement, and performance. Designing an optimal mix for SCC can be more complex compared to conventional concrete. Achieving the right balance between flowability, stability, and strength requires careful consideration of various parameters, including the type and proportion of ingredients, viscosity, and rheology. The selection and proportioning of materials, including high-range water reducers (superplasticizers), viscosity-modifying agents, and fine aggregates, are critical for the success of SCC. Improper selection or proportions can lead to issues such as segregation, bleeding, or reduced strength. (Domone, 2006)

From its origins over 10,000 years ago, burnt bricks have been integral to human construction practices. Since the advent of full brick variants in 1964, bricks have revolutionized construction, blending functionality with aesthetics. Despite advancements in materials, bricks still remains indispensable as one of the most commonly used construction material. (Fiala et al., 2019). Again, it is to be considered that the manufacturing of bricks, whether using clay or fly ash, contributes significantly to greenhouse gas emissions due to high-energy kiln firing, reliance on coal and cement, transportation emissions, and waste generation. (Joglekar et al., 2018)

A significant part of waste generation is caused by the building and construction industry.(Bossink & Brouwers, 1996). Construction and demolition (C&D) waste, holding one of the key portions in waste generation in the present world, is anticipated to increase further in the future due to ongoing urbanization and construction activities. Recycling C&D waste has been recognized as a valuable option for minimizing the volume of waste sent to landfills and reducing the strain on natural resources by mitigating primary mineral resource depletion. By repurposing materials from demolished structures and recycling construction waste, not only can the environmental impact of waste disposal be reduced, but valuable resources can also be conserved for future use, promoting sustainability in the construction industry. (Knoeri et al., 2011)

The importance of resource efficiency and recycling is highly emphasized in the context of a sustainable supply mix of aggregates for the construction industry. (Blengini et al., 2012) Recycling brick aggregates as Coarse Aggregates (CA) in concrete mix can help conserve natural resources, as it reduces the demand for new raw materials. By reusing bricks from demolished structures as CA, we can extend the lifespan of the existing resources. It can reduce the overall costs associated with construction projects, making it an economically viable option. Recycling brick aggregates can also help lower the carbon footprint associated with construction activities by decreasing the need for new brick production leading to lower energy consumption and associated greenhouse gas emissions.

Certain types of aggregates may not be suitable for use in SCC due to their shape, size, or absorption characteristics. Incompatible, especially recycled aggregates can lead to issues such as bleeding, segregation, or a decrease in strength.(Tang et al., 2020) Recycled brick aggregates may exhibit greater variability in terms of particle size, shape, and composition compared to virgin aggregates. The higher water absorption and porous structure of Recycled Brick Aggregate (RBA) are the main challenges for the application of RBA in Self Compacting Concrete (SCC) that requires high fluidity and good mechanical strength. (Cachim, 2009) The incorporation of RBA decreases the flowability and passing ability of SCC. This can impact the water-to-cement ratio in the concrete mix, affecting workability, setting time, and overall performance and also leading to potential issues with consistency. (Rashid et al., 2009) The presence of weaker or deteriorated bricks in the recycled aggregate mix can result in lower compressive strength and reduced durability of the concrete. Recycled brick aggregates may contain contaminants, such as mortar, paint, or other impurities, which can adversely affect the properties of the concrete. Contaminants may weaken the bond between the recycled aggregate and the cement paste, leading to reduced strength and durability. (De Juan & Gutiérrez, 2009)

Self-Compacting Concrete (SCC) prepared with recycled aggregate has not been extensively studied yet. In particular, in the last few years some researches have been made using Construction and demolition waste in SCC, particularly with coarse recycled concrete aggregates. (Manzi et al., 2017) This paper addresses this challenge of using recycled brick aggregate to make conventional Self-compacting concrete.

1.3 Objectives of the Study

In this study, we embark on a quest to find ways of producing self-compacting concrete using recycled brick aggregate. The primary objectives of this study will be:

- To determine whether recycled brick aggregate can be a considered an alternative to stone aggregates for preparing Self Compacting Concrete.

- To ensure a sustainable supply of aggregates for future construction purposes.

1.4 Research Flow Diagram

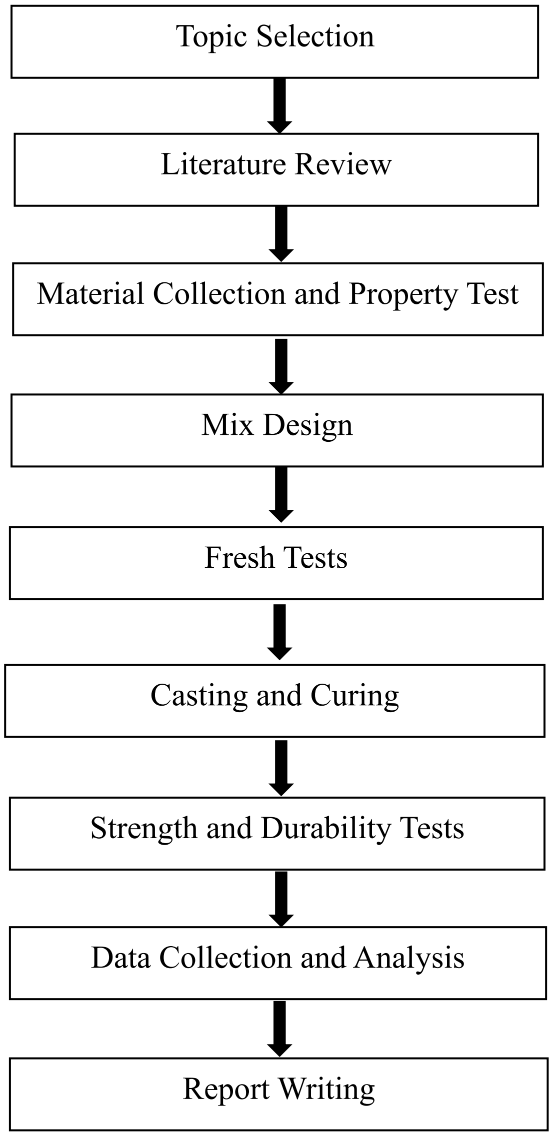

Figure 1 Research Flow Diagram

1.5 Layout of the Thesis

The thesis consists of the following layout:

Chapter 1: Introduction – The current chapter, that discusses about the theory, background, objectives, scope of the study, research flow diagram.

Chapter 2: Literature Review – The chapter describes the related research in the field of our study by former authors and their findings.

Chapter 3: Methodology - This chapter describes the procedures and steps that were followed to conduct our study.

Chapter 4: Results and Discussion - Collected data and processing of the data, results were included in the chapter.

Chapter 5: Conclusion and Recommendations - General discussion, limitations, recommendations and future scopes of work was discussed here.

Chapter 2: Literature Review

Studying the long-term properties of Self-compacting concrete (SCC) with recycled concrete aggregate it is found that it is feasible to produce SCC with coarse and fine recycled concrete aggregates up to 40% volume in the mix design.(Manzi et al., 2017) Recycled brick aggregates (RBA) generally have inferior quality such as lower density and higher water absorption capacity compared to natural aggregates (NA). (Dhir et al., 1999) The properties and characteristics of recycled aggregate is directly influenced by the quality of original aggregate, quality and amount of the original cement mortar, crushing process and the deterioration degree of the original concrete. (Tang et al., 2020) When using recycled fine aggregates concrete might develop strength at a slower rate and exhibit higher shrinkage compared to natural aggregate concrete. Up to a 30% replacement ratio of fine recycled concrete aggregates would not compromise the mechanical properties of concrete. (Khatib, 2005)

Poor segregation resistance of SCC can lead to poor deformability and blockage around congested reinforcement. A paper by Zhang showed that the replacement of natural aggregates with recycled fine clay brick aggregate decreases the flowability, passing ability and segregation resistance. (Zhang et al., 2021) To counter this issue high powder content, such as limestone powder or fly ash, or the use of viscosity agents, is commonly employed and proven to enhance segregation resistance. (Khayat, 1999) A paper by SC Kou and CS Poon highlights the properties of self-compacting concrete prepared with coarse and fine recycled concrete aggregates which shows that the addition of fly ash increased slump flow and blocking ratio while the compressive strengths of the mixtures prepared without the addition of fly ash decreased with increasing fine recycled aggregate content. Again, the resistance to chloride ion penetration increased with an increase in the fine recycled aggregate content. (Kou & Poon, 2009) Incorporating rejected fly ash in SCC can replace viscosity agents. Benefits observed include shortened flow time, lowered air content, increased compressive strength and elastic modulus, and improved bleeding and segregation resistances. (Poon & Ho, 2004)

A paper by S. Venkateswara Rao used higher volumes of fly ash as high as 50-70% was added in total powder to generate SCC. It was noted that the fresh properties improved with increase in fly ash percentages. It was also noted that the optimum dosages of fly ash were 52% addition in case of standard grade SCC and it is 31% addition in case of high strength Self Compacting Concrete. (Rao et al., 2010) Another paper by Heba A. Mohamed showed that the higher the percentage of Fly Ash (FA) the higher the values of concrete compressive strength until 30% of FA with mix design. However, the highest value of concrete compressive strength is obtained from mix containing 15% Silica Fume (SF). (Mohamed, 2011) A paper by Sasanipour and Aslani showed that Silica fume increased the workability and improved the fresh properties of SCCs. However, the mixes lacking silica fume had good fresh properties and appropriate passing ability. (Sasanipour et al., 2019)

The addition of slag by substitution to cement was found very beneficial to fresh self-compacting concrete. At constant water/powder ratio and superplasticizer content, an improvement of workability was observed up to 20% of slag content with an optimum content of 15%. Workability retention of about 60 min with 15% of slag content was obtained.(Boukendakdji et al., 2009). The presence of FA, Ground granulated blast furnace slag increased the initial slump flow and reduced the slump flow loss rate, wet density of the SCC and prolonged the setting times of cement paste, but did not have any obvious effect on the flowability and stability of the SCC. (Zhao et al., 2015) A paper by Li Jianyong and Tian Pei highlighted the appropriate dosage of slag and silica fume are both 10-15% of the total weight of bonding materials in concrete. (Jianyong & Pei, 1997)

Partial replacement of OPC by FA and SF in SCC reduces the surface water absorption and sorptivity. When only fly ash is used to partially replace OPC, the reduction in sorptivity is noticeable when the amount of FA is greater than 20% replacement of OPC. When both FA and SF are adopted in SCC mixes, the reduction in water absorption is higher than using FA alone. (Leung et al., 2016) A paper by Ovbeniyekede observed from the water absorption test, the percentage of water absorption was least at 30% replacement of sand with quarry dust and 10% replacement of cement with fly ash. The water absorption value of self-compacting concrete containing quarry dust and fly ash was generally lower compared to the one containing no quarry dust and fly ash (Ovbeniyekede et al., 2018)

A paper by Mohammed Abdur Rashid observed that the unit weight of concretes made with crushed bricks is around 130 pounds per cu ft which is about 13% lower than that of normal weight concrete. The cylinder compressive strength has been found about 90% of the corresponding cube compressive strength for brick aggregate concretes studied. (Rashid et al., 2009) A paper on Recycling of Brick Aggregate Concrete as Coarse Aggregate by Dr. Mohammed Tarek Uddin observed the comparison with the first-class brick aggregate commonly used in Bangladesh, the recycled aggregates showed better performance with respect to abrasion and absorption capacity. For W/C = 0.55, the recycled aggregate concrete gives lower strength compared with the first-class brick aggregate concrete. If W/C is reduced (from 0.55 to 0.45), the strength and Young's modulus of concrete are improved significantly. The average strength of recycled aggregate concrete is found to be 24.7 and 20.4 MPa for W/C = 0.45 and 0.55, respectively. (Mohammed et al., 2015) A paper by I.M Nikbin studying the comprehensive investigation into the effect of water to cement ratio and powder content on mechanical properties of self-compacting concrete found that with increase of w/c ratio from 0.35 to 0.7 the value of compressive strength is decreased by 66% and tensile strength of SCC is decreased by 51%. (Nikbin et al., 2014)

Chapter 3: Methodology

3.1 Material Properties

3.1.1 Specific Gravity of Materials

For the thesis purpose the following materials were selected as shown in **Table 1**:

Table 1: Specific Gravity of Materials

Specific Gravity	
Sp Gravity Of Natural Sand, Gns	2.54
Sp Gravity Of Recycled Sand, Grs	2.10
Sp Gravity Of Course Recycled Bick Aggregate, Grba	2.12
Sp Gravity Of Cement, Gc	3.10
Sp Gravity Of Fly Ash, Gfa	1.90
Sp Gravity Of Slag, Gsa	2.71
Sp Gravity Of Silica Fume, Gsf	2.2
Sp Gravity Of Water, Gw	1

3.1.2 Aggregate Grading

According **ASTM C33** standards aggregates of Grading-67 and Grading-7 were used

TABLE 2 Grading Requirements for Coarse Aggregates

Size Number	Nominal Size (Sieves with Square Openings)	Amounts Finer than Each Laboratory Sieve (Square-Openings), Mass Percent													
		100 mm (4 in.)	90 mm (3½ in.)	75 mm (3 in.)	63 mm (2½ in.)	50 mm (2 in.)	37.5 mm (1½ in.)	25.0 mm (1 in.)	19.0 mm (¾ in.)	12.5 mm (½ in.)	9.5 mm (⅜ in.)	4.75 mm (No. 4)	2.36 mm (No. 8)	1.18 mm (No. 16)	300 µm (No.50)
1	90 to 37.5 mm (3½ to 1½ in.)	100	90 to 100	...	25 to 60	...	0 to 15	...	0 to 5	...	...	...	...	...	...
2	63 to 37.5 mm (2½ to 1½ in.)	...	...	100	90 to 100	35 to 70	0 to 15	...	0 to 5	...	...	...	...	...	...
3	50 to 25.0 mm (2 to 1 in.)	...	...	...	100	90 to 100	35 to 70	0 to 15	...	0 to 5	...	...	...	...	...
357	50 to 4.75 mm (2 in. to No. 4)	...	...	...	100	95 to 100	...	35 to 70	...	10 to 30	...	0 to 5	...	...	...
4	37.5 to 19.0 mm (1½ to ¾ in.)	...	...	...	...	100	90 to 100	20 to 55	0 to 15	...	0 to 5	...	...	...	...
467	37.5 to 4.75 mm (1½ in. to No. 4)	...	...	...	...	100	95 to 100	...	35 to 70	...	10 to 30	0 to 5	...	...	...
5	25.0 to 12.5 mm (1 to ½in.)	...	...	...	...	...	100	90 to 100	20 to 55	0 to 10	0 to 5	...	...	...	...
56	25.0 to 9.5 mm (1 to ⅜ in.)	...	...	...	...	...	100	90 to 100	40 to 85	10 to 40	0 to 15	0 to 5	...	...	...
57	25.0 to 4.75 mm (1 in. to No. 4)	...	...	...	...	...	100	95 to 100	...	25 to 60	...	0 to 10	0 to 5	...	...
6	19.0 to 9.5 mm	...	...	...	...	...	...	100	90 to 100	20 to 55	0 to 15	0 to 5	...	...	...
67	19.0 to 4.75 mm (¾ in. to No. 4)	...	...	...	...	...	...	100	90 to 100	...	20 to 55	0 to 10	0 to 5	...	...
7	12.5 to 4.75 mm (½ in. to No. 4)	...	...	...	...	...	...	...	100	90 to 100	40 to 70	0 to 15	0 to 5	...	...
	(⅜ in. to No. 8)														...
89	9.5 to 1.18 mm (⅜in. to No. 16)	...	...	...	...	...	...	...	...	100	90 to 100	20 to 55	5 to 30	0 to 10	0 to 5
9[A]	4.75 to 1.18 mm (No. 4 to No. 16)	...	...	...	...	...	...	...	...	...	100	85 to 100	10 to 40	0 to 10	0 to 5

[A] Although size 9 aggregate is defined in Terminology C 125 as a fine aggregate, it is included as a coarse aggregate when it is combined with a size 8 material to create a size 89, which is a coarse aggregate as defined by Terminology C 125.

Figure 2 *Aggregate Grading ASTM C33*

For 20 mm Downgrade aggregates Grading 67 of ASTM C33 was used as per **Table 2**

Table 2 Grading 67 - ASTM C33

Grading 67			
19 mm to 4.75 mm			
Sieve Size	**% Passing**	**Cumulative % Retained**	**% Retained**
25 mm	100.00	0.00	0.00
19 mm	95.00	5.00	5.00
9.5 mm	37.50	62.50	57.50
4.75 mm	5.00	95.00	32.50
2.36 mm	0.00	100.00	5.00

For 15 mm Downgrade aggregates Grading 7 of ASTM C33 was used as per **Table 3**

Table 3 Grading 7 - ASTM C33

Grading 7			
12.5 mm to 4.75 mm			
Sieve Size	**% Passing**	**Cumulative % Retained**	**% Retained**
19 mm	100	0	0
12.5 mm	95	5	5
9.5 mm	55	45	40
4.75 mm	7.5	92.5	47.5
2.36 mm	2.5	97.5	5
1.1 mm	0	100	2.5

3.2 Details of Cases Investigated

3.2.1 Total Cases

The following cases were set for the thesis purpose according to **Table 4**

Table 4 Total Cases

Case No.	15mm downgrade	20 mm downgrade
1	100% RBA + 100% RS + OPC + FA + Sl	100% RBA + 100% RS + OPC + FA + Sl
2	100% RBA + 100% NS + OPC + FA + Sl	100% RBA + 100% NS + OPC + FA + Sl
3	100% RBA + 100% RS + OPC + FA + Sl +SF	100% RBA + 100% RS + OPC + FA + Sl +SF
4	100% RBA + 100% NS + OPC + FA + Sl +SF	100% RBA + 100% NS + OPC + FA + Sl +SF
5	100% RBA + 100% RS + OPC (500)	100% RBA + 100% RS + OPC (500)

Where,

Table 5 Material Abbreviation

OPC	Ordinary Portland Cement
RBA	Recycled Brick Aggregate
RS	Recycled Sand
NS	Natural Sand
FA	Fly Ash
Sl	Slag
SF	Silica Fume

The cases were primarily divided into parts based on aggregate grading of **15 mm Downgrade** and **20 mm Downgrade**. Both **Natural Sand (NS)** and **Recycled Sand (RS)** were used separately for both gradings to compare the traditional concrete properties and also to investigate the feasibility and performance of recycled materials in SCC respectively. For cementitious materials **Ordinary Portland Cement (OPC)** was used as a control mix to benchmark the performance of other mixes. Partial replacement with cementitious materials was done with slag, fly ash and silica fume for its potential to enhance flow, durability and improving workability.

A total of different mix combinations was explored for both aggregate gradings, incorporating either natural or recycled sands, and different supplementary cementitious materials. These combinations were designed to assess the suitability of recycled brick aggregates in SCC, focusing on both sustainability and performance. These combinations were as follows:

Pure OPC Mix: This baseline mix consisted solely of OPC as the binder to evaluate the fundamental properties of SCC with RBA.

<u>**OPC with Partial Replacement**</u>:

OPC + Slag + Fly Ash: In this mix, OPC was partially replaced with a combination of slag and fly ash. This blend aimed to enhance both the flow properties and durability of the concrete.

OPC + Slag + Fly Ash + Silica Fume: This mix involved an additional replacement of OPC with silica fume, along with slag and fly ash. The inclusion of silica fume was intended to further improve the concrete's compressive strength and resistance to chemical attacks.

3.2.2 Mix Design

The mix design for all the cases were set as follows as shown in **Table 6**

Table 6 Mix design

Case	**S/A**	**W/C**	**Binder (kg/m^3)**				**Water (kg/m^3)**	**RBA (kg/m^3)**	**NS (kg/m^3)**	**RS (kg/m^3)**
			OPC (kg/m^3)	**FA (kg/m^3)**	**Sl (kg/m^3)**	**SF (kg/m^3)**				
1 (15)	0.5	0.35	300	61.29	87.42	0	175	682.33	0	675.9
1 (20)	0.5	0.35	300	61.29	87.42	0	175	682.33	0	675.9
2 (15)	0.5	0.35	300	61.29	87.42	0	175	682.33	817.51	0
2 (20)	0.5	0.35	300	61.29	87.42	0	175	682.33	817.51	0
3 (15)	0.5	0.35	250	61.29	87.42	35.48	175	682.33	0	675.9
3 (20)	0.5	0.35	250	61.29	87.42	35.48	175	682.33	0	675.9
4 (15)	0.5	0.35	250	61.29	87.42	35.48	175	682.33	817.51	0
4 (20)	0.5	0.35	250	61.29	87.42	35.48	175	682.33	817.51	0
5 (15)	0.5	0.35	500	0	0	0	175	682.33	0	675.9
5 (20)	0.5	0.35	500	0	0	0	175	682.33	0	675.9

For all cases, the water-to-cement ratio (**W/C**) and the sand-to-aggregate ratio (**S/A**) were fixed at **0.35** and **0.5**, respectively. The cement content was set at **500 kg/m³.** Partial replacements included 20% slag, 20% fly ash, and 10% silica fume of the OPC content.

3.2.3 Trial Mixes

The trial mix for all the cases were set as follows as shown in **Table 7**

Table 7 Trial Mixes

Case	Trial Volm. m^3	Admixture (%)	OPC, kg	FA, kg	Sl, kg	SF, kg	Water, kg	RBA, kg	NS, kg	RS, kg	Admixture, gm
1 (15)	0.035	0.95	10.50	2.15	3.06	0.00	6.13	23.88	0.00	23.66	149.20
1 (20)	0.035	1.1	10.50	2.15	3.06	0.00	6.13	23.88	0.00	23.66	172.75
2 (15)	0.035	0.7	10.50	2.15	3.06	0.00	6.13	23.88	28.61	0.00	109.93
2 (20)	0.035	1	10.50	2.15	3.06	0.00	6.13	23.88	28.61	0.00	157.05
3 (15)	0.035	1.4	8.75	2.15	3.06	1.24	6.13	23.88	0.00	23.66	195.37
3 (20)	0.035	1.3	8.75	2.15	3.06	1.24	6.13	23.88	0.00	23.66	181.41
4 (15)	0.035	0.9	8.75	2.15	3.06	1.24	6.13	23.88	28.61	0.00	125.59
4 (20)	0.035	1.2	8.75	2.15	3.06	1.24	6.13	23.88	28.61	0.00	167.46
5 (15)	0.035	1.1	17.50	0.00	0.00	0.00	6.13	23.88	0.00	23.66	192.50
5 (20)	0.035	1.3	17.50	0.00	0.00	0.00	6.13	23.88	0.00	23.66	227.50

The trial volume was consistently maintained at **0.035 m^3** for all cases. The dosage of admixture was adjusted as necessary to achieve the desired flow properties. These dosages were calculated based on the total binder content in each respective mix.

3.3 Fresh Tests

The following fresh tests were conducted as shown in **Table 8**

Table 8 Fresh Test

Test Name	**Volume (m3)**	**Standards**
Flow Test	0.008	ASTM-C 1611C-1611M–05
J Ring	0.008	ASTM-C 1621-C 1621M-06
V Funnel	0.012	UTC-0540

3.3.1 Flow Test

Figure 3 *Flow Test*

Slump Flow Test is used to evaluate the flowability and stability of self-compacting concrete (SCC). In this test, a standard Abrams cone is placed on a flat, moistened base plate and filled with the concrete mix. The cone is then lifted vertically to allow the concrete to flow outward freely. The horizontal spread of the concrete is measured in two perpendicular directions, average of the slump flow spread **diameter (d1 & d2)** of two perpendicular direction is measured, which indicates the concrete's flowability. The slump flow time **T500** is also measured (the time period between the moment the cone leaves the base plate and the SCC first touches the circle of diameter 500 mm). This test provides both quantitative and qualitative measures of SCC's performance, ensuring it has the necessary characteristics for easy placement without mechanical consolidation.

3.3.2 J-Ring Test

Figure 4 *J-Ring Test*

The J-Ring Test is utilized to evaluate the ability of self-compacting concrete (SCC) to navigate through complex formwork and reinforcement, maintaining homogeneity and structural integrity. In this test, a J-Ring, which consists of a ring with evenly spaced vertical rods, is placed around a standard slump cone on a flat, moistened base plate. The slump cone is filled with the SCC mix in one continuous pour, without any compaction. The cone is then lifted vertically, allowing the concrete to flow outward and pass through the rods of the J-Ring.

The spread of the concrete is measured in two perpendicular directions to determine the **average diameter**, similar to the slump flow test. The difference in **height** between the concrete just inside J-Ring bars and outside J-Ring bars is measured. The time to reach 500 mm diameter (**T500**) is also measured.

3.3.3 V-Funnel Test

V-Funnel Test is employed to assess the flow time and viscosity of self-compacting concrete (SCC). In this test, the V-funnel apparatus, which is a metal funnel with a specified V-shaped cross-section, is used. The funnel is initially checked for cleanliness and then moistened. The SCC mix is poured into the funnel without compaction, and the bottom outlet is quickly opened to allow the concrete to flow out. Two types of flow time are recorded as per **Flow time immediately** (open the trap after 5 sec of filling the apparatus) and **Flow time at T5 minutes** (fill and wait for 5 minutes to start discharge). This flow time provides a measure of the concrete's viscosity and ability to flow under its own weight. A shorter flow time indicates lower viscosity and higher fluidity, whereas a longer flow time suggests higher viscosity and potential challenges in flowability.

Figure 5 *V-Funnel Test*

3.3.4 Fresh Test Result Comparison

The result of the flow test is compared based on the **Table 9** given below for self-compacting concrete. (Aggarwal et al., 2008)

Table 9 Fresh Test Result Comparison

1	**Slump Flow Diameter:**	500-700mm
2	**T500:**	2-5s
3	**V-funnel:**	6-12s

3.4 Strength and Durability Tests

The following Strength and Durability tests were conducted as shown in **Table 10**

Table 10 Strength and Durability Tests

Test Name	No. of Cylinders tested	Standard
Compressive Strength Test	3 (per case)	ASTM C39
Ultrasonic Pulse Velocity (UPV)	3 (per case)	ASTM C597
Rapid Chloride Penetration Test (RCPT)	1 (per case)	ASTM C1202
Scanning Electron Microscopy (SEM)	1 (per case)	ASTM C1723-16

For each of the 10 formulated cases, a total of 15 cylinders were cast, resulting in 150 castings overall. Of the 15 cylinders per case, 12 were dedicated to compressive strength testing, with tests conducted at specified intervals. The Ultrasonic Pulse Velocity (UPV) test was performed on these same cylinders before conducting the compressive strength tests, thereby eliminating the need for additional cylinders. Additionally, one extra cylinder was cast for each case to facilitate the Rapid Chloride Penetration Test (RCPT) and another extra cylinder for Scanning Electron Microscopy (SEM) analysis. An extra cylinder was kept for each case for precautionary purposes.

3.4.1 Compressive Strength Test

__Figure 6__ Compressive Strength Test

For the purpose of compressive strength test concrete samples were prepared and cast into molds of cylinders of 100 mm diameter and 200 mm height. After casting, the samples are allowed to cure under controlled conditions. Testing age was selected at 7-, 14-, 28- and 90-days intervals respectively. Once the curing period is complete, the samples are subjected to a compressive load using a universal testing machine. The load is applied uniformly at a constant rate until the sample fails. The maximum load at failure is recorded, and the compressive strength is calculated by dividing this load by the cross-sectional area of the sample. This test is essential for assessing the concrete's capacity to endure axial loads, serving as a primary indicator of its structural performance and overall quality. The results ensure that the SCC meets the specified strength requirements.

The details of number of cylinders casted for each case is shown in **Table 11**

Table 11 Compressive Strength Test

Cylinder Volume (0.001647 m3)	
Days	**Cylinders Casted (For Average)**
7	3
14	3
28	3
90	3

For each 7-,14-,28-, 90-days interval, a total of three cylinders were tested for each case, and the average compressive strength was recorded in megapascals (**MPa**).

3.4.2 Ultrasonic Pulse Velocity (UPV)

Ultrasonic Pulse Velocity (UPV) test is a nondestructive test used to examine the homogeneity, quality, cracks, cavities, and defects in concrete. It measures the time it takes for a pulse of vibrational energy to travel through a concrete member. The vibrational energy is introduced into the concrete by the transmitting transducer, which is coupled to one surface. The direct path length between the transducers is divided by the travel time to obtain the pulse velocity through the concrete. The readings were taken in **µs** and **m/s**.

***Figure** 7 Ultrasonic Pulse Velocity (UPV)*

3.4.3 Rapid Chloride Penetration Test (RCPT)

The Rapid Chloride Penetration Test (RCPT) is used to evaluate the permeability of concrete to chloride ions. Cylinders were sawn in 50 mm thick slice specimens for the test purpose. Specimen were allowed to surface dry for at least 1 Hour and then it was stored in a vacuum chamber for 3 hours while the pressure was 1-5 kPa. The chamber was filled with saturated $Ca(OH)_2$ solution while keeping the vacuum pump running. Then again keep the vacuum pump was kept on for another 1 hour before turning it off. Then the specimen was soaked under water for 18 hours in the vacuum chamber.

***Figure 8** Rapid Chloride Penetration Test (RCPT)*

First a disc of concrete was placed on the cell. The side of top surface was then filled with 3% NaCl solution and this side was connected with negative terminal. The other side was filled with 0.3N NaOH solution and connected with the positive terminal. The voltage was set at 60V. The current readings (**A**) were recorded for six hours at 30 minutes interval.

The calculation for the RCPT result was done using the following formula:

$$Q = 900\ (I_0 + 2I_{30} + 2I_{60} + \cdots + 2I_{300} + 2I_{330} + I_{360})$$

Equation 1 *RCPT Calculation Formula*

Where,

Q = charge passed (coulombs),

I_0 = current (amperes) immediately after voltage is applied

I_t = current (amperes) at t min after voltage is applied

The interpretation of the result was done using the following **Table 12**

Table 12 Chloride Ion Penetrability based on Charge Passed

Charge Passed (Coulombs)	Chloride Ion Penetrability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

3.4.4 Scanning Electron Microscopy (SEM)

In this test the samples were investigated by taking images of the microstructure of samples using TESCAN VEGA3 SEM. Freshly broken pieces of mortar and concrete were collected immediately after crushing of the specimens during test for compressive strength. The samples were dried for 2 hours at 60^{O}C. Then the samples were immersed in an acetone solution for removing dusts from the surface. The samples were coated with gold sputtering to avoid charge surging during SEM investigation under high voltage

Figure 9 *Scanning Electron Microscopy (SEM)*

Chapter 4: Results and Analysis

4.1 Fresh Test Results

4.1.1 Flow Test Result

The diameters obtained from flow test result in descending order are shown in the **Table 13** below

Table 13 Flow Test Result

Case no	Details	Diameter (mm)
1 (20)	100% RBA + 100% **RS** + OPC + FA + Sl	**732.5**
3 (20)	100% RBA + 100% **RS** + OPC + FA + Sl +SF	**690**
1 (15)	100% RBA + 100% **RS** + OPC + FA + Sl	**687.5**
5 (15)	100% RBA + 100% **RS** + OPC (500)	**677.5**
2 (15)	100% RBA + 100% **NS** + OPC + FA + Sl	**667.5**
4 (20)	100% RBA + 100% **NS** + OPC + FA + Sl +SF	**625**
2 (20)	100% RBA + 100% **NS** + OPC + FA + Sl	**620**
4 (15)	100% RBA + 100% **NS** + OPC + FA + Sl +SF	**612.5**
3 (15)	100% RBA + 100% **RS** + OPC + FA + Sl +SF	**605**
5 (20)	100% RBA + 100% **RS** + OPC (500)	**535**

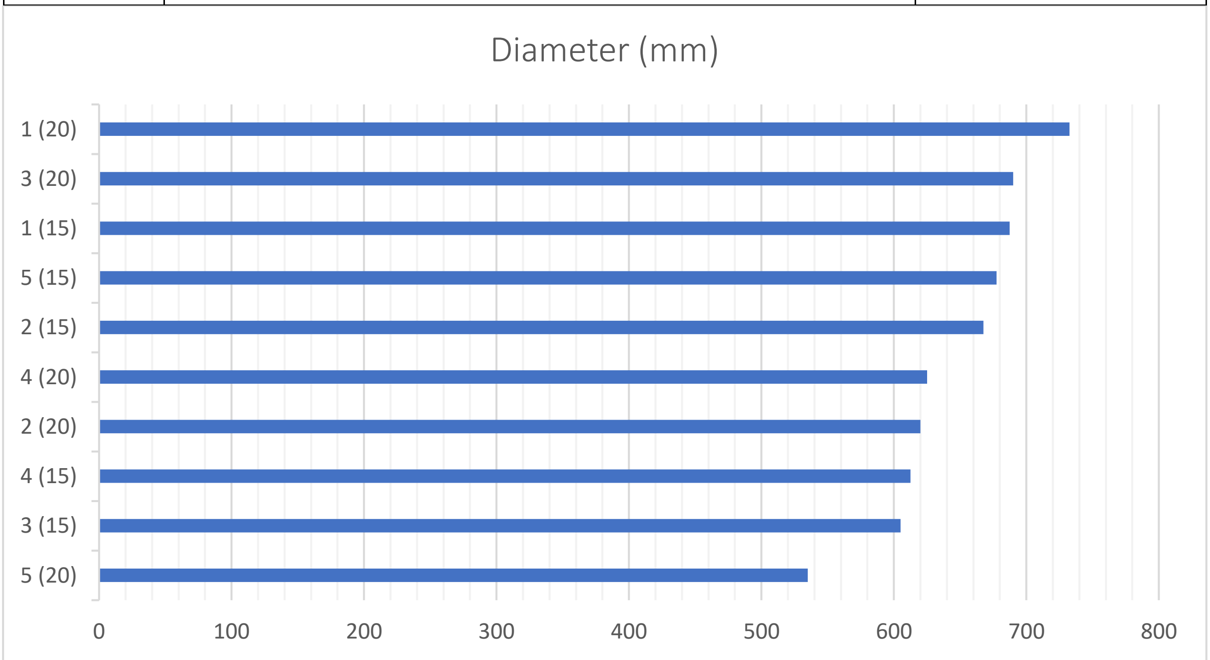

Figure 10 *Flow test Result*

The results indicate that the highest flow diameter was achieved with recycled sand combined with fly ash and slag in mixes with 20 mm downgrade aggregate size. A consistent pattern emerged, demonstrating that recycled sand enhances flowability more effectively than natural sand. Additionally, mixes with 20 mm downgrade aggregates exhibited better flow than those with 15 mm downgrade aggregates. The lowest flow was recorded in Case-5(20), which involved a pure OPC mix with recycled sand and 20 mm downgrade aggregates. Notably, all cases exceeded the 500 mm flow diameter benchmark, with all natural sand cases averaging a satisfactory flow diameter surpassing the 600 mm mark. However, the inclusion of silica fume tended to reduce flowability compared to mixes incorporating only fly ash and slag.

4.1.2 J-Ring Test Result

The diameters obtained from J-Ring test result in descending order are shown in the **Table 14** below

Table 14 J-Ring Test Result

Case no	Details	Diameter (mm)
1 (20)	100% RBA + 100% **RS** + OPC + FA + Sl	**687.5**
2 (15)	100% RBA + 100% **NS** + OPC + FA + Sl	**657.5**
2 (20)	100% RBA + 100% **NS** + OPC + FA + Sl	**570**
4 (20)	100% RBA + 100% **NS** + OPC + FA + Sl +SF	**550**
1 (15)	100% RBA + 100% **RS** + OPC + FA + Sl	**520**
3 (20)	100% RBA + 100% **RS** + OPC + FA + Sl +SF	**515**
4 (15)	100% RBA + 100% **NS** + OPC + FA + Sl +SF	**512.5**
5 (15)	100% RBA + 100% **RS** + OPC (500)	**510**
3 (15)	100% RBA + 100% **RS** + OPC + FA + Sl +SF	**505**
5 (20)	100% RBA + 100% **RS** + OPC (500)	- (did not pass)

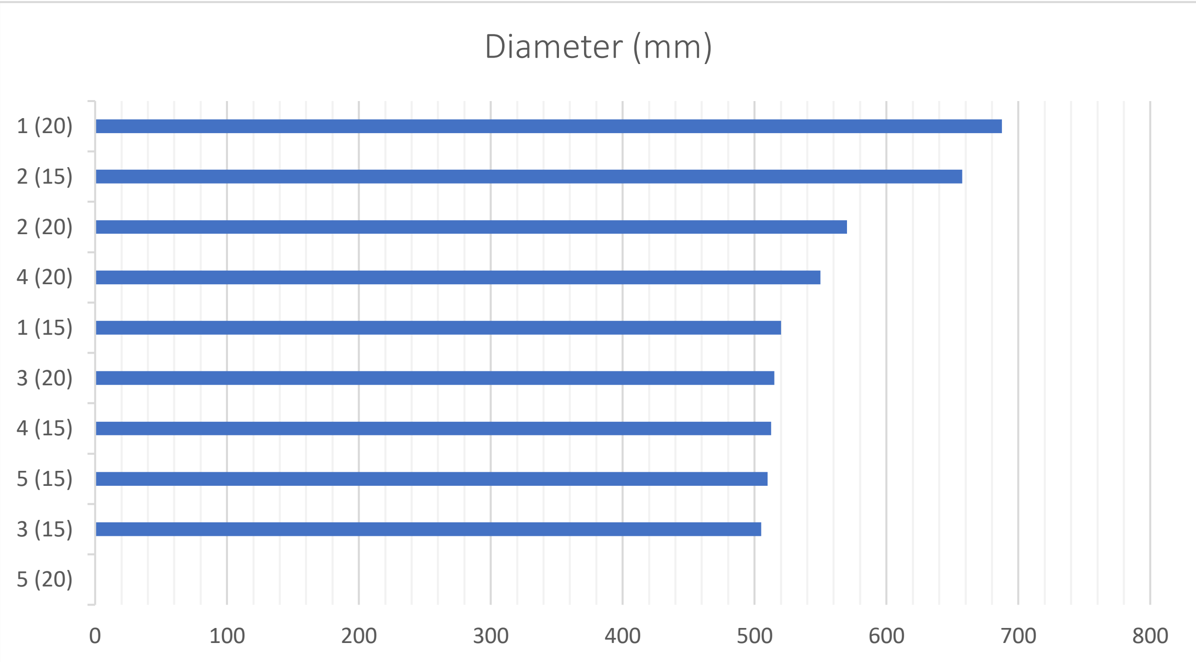

Figure 11 *J-Ring Test Result*

Similar results can also be observed in case of J-ring test where the highest flow diameter was obtained with recycled sand combined with fly ash and slag in with mixes 20 mm downgrade aggregate size. The second highest flow is obtained from Case-2 (15) with a natural sand case combined with fly ash and slag in mixes with 15 mm downgrade aggregate size. In case of J-Ring natural sand cases tended to show better flowability results compared to recycled sand cases. Only one case, Case-5 (20) for 20 mm downgrade aggregate and pure OPC with recycled sand failed to pass the J-ring and reach the 500 mm mark.

4.1.3 V-Funnel Test Result

The time obtained from V-Funnel test result in ascending order for **T0** are shown in the **Table 15** below

Table 15 V-Funnel T0 Result

Case no	Details	Time (sec)
2 (15)	100% RBA + 100% **NS** + OPC + FA + Sl	**6.9**
1 (15)	100% RBA + 100% **RS** + OPC + FA + Sl	**9.6**
5 (15)	100% RBA + 100% **RS** + OPC (500)	**10**
4 (20)	100% RBA + 100% **NS** + OPC + FA + Sl +SF	**13**
4 (15)	100% RBA + 100% **NS** + OPC + FA + Sl +SF	**14**
2 (20)	100% RBA + 100% **NS** + OPC + FA + Sl	**15.2**
1 (20)	100% RBA + 100% **RS** + OPC + FA + Sl	**17**
3 (15)	100% RBA + 100% **RS** + OPC + FA + Sl +SF	**17.5**
3 (20)	100% RBA + 100% **RS** + OPC + FA + Sl +SF	**18**
5 (20)	100% RBA + 100% **RS** + OPC (500)	**22**

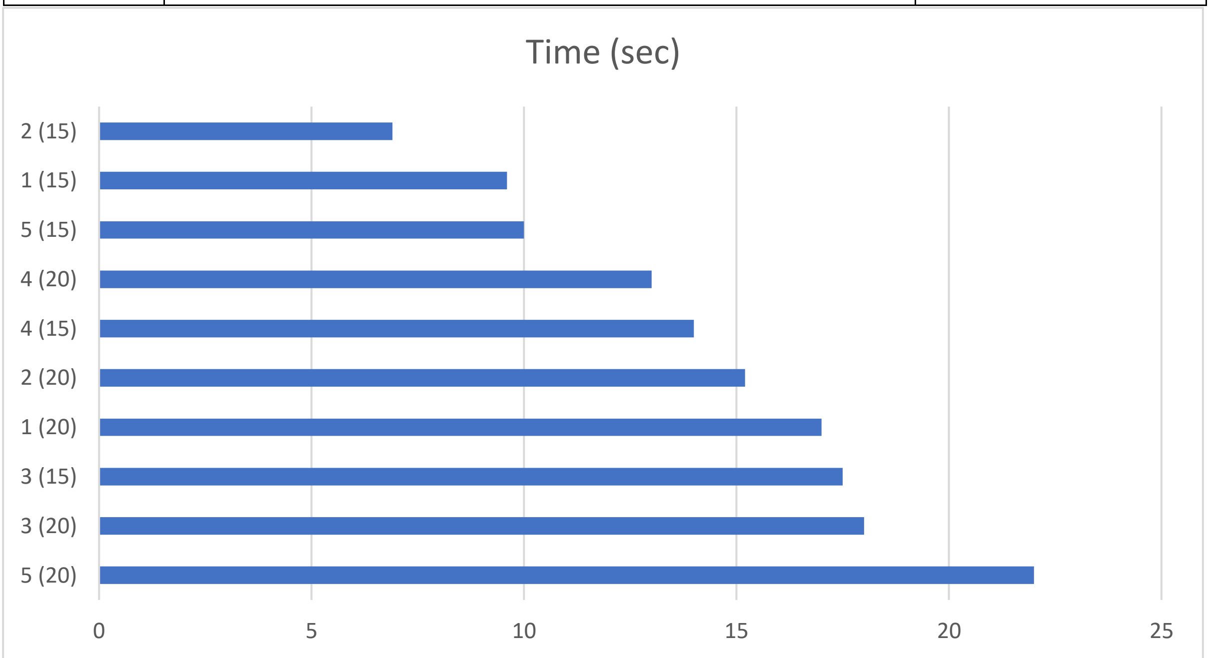

Figure 12 *V-Funnel T0 Result*

The time obtained from V-Funnel test result in ascending order for **T5** are shown in the **Table 16** below

Table 16 V-Funnel T5 Result

Case no	Details	Time (sec)
2 (15)	100% RBA + 100% **NS** + OPC + FA + Sl	**7.5**
1 (15)	100% RBA + 100% **RS** + OPC + FA + Sl	**10.3**
5 (15)	100% RBA + 100% **RS** + OPC (500)	**12.45**
4 (20)	100% RBA + 100% **NS** + OPC + FA + Sl +SF	**14.3**
2 (20)	100% RBA + 100% **NS** + OPC + FA + Sl	**16.3**
4 (15)	100% RBA + 100% **NS** + OPC + FA + Sl +SF	**18**
1 (20)	100% RBA + 100% **RS** + OPC + FA + Sl	**38**
3 (15)	100% RBA + 100% **RS** + OPC + FA + Sl +SF	**40**
3 (20)	100% RBA + 100% **RS** + OPC + FA + Sl +SF	**41**
5 (20)	100% RBA + 100% **RS** + OPC (500)	**-** (did not Pass)

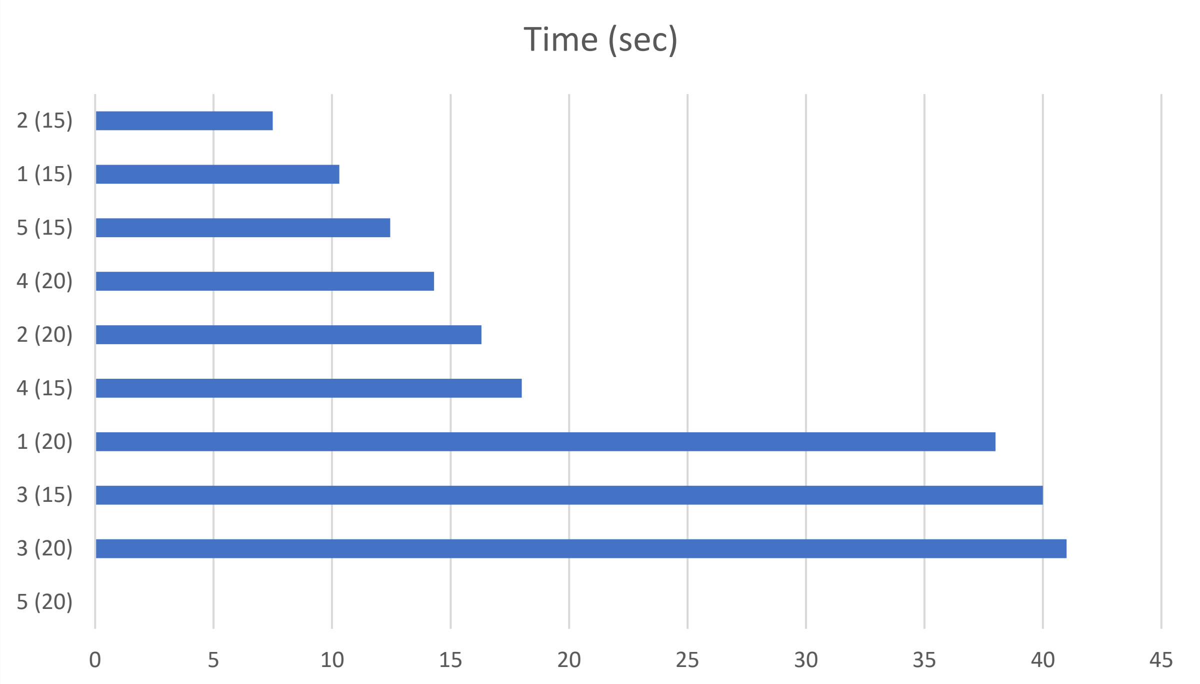

***Figure 13** V-Funnel T5 Result*

In both T0 and T5 measurements, Case-2(15), which incorporates natural sand with slag and fly ash using 15 mm downgrade aggregates, required the least time. The second shortest time was observed in Case-1(15), with recycled sand combined with fly ash and slag using 15 mm downgrade aggregates. The third shortest time was recorded for the pure OPC case with 15 mm downgrade aggregates. These three cases also met the 6-12 seconds requirement for both T0 and T5. Overall, 15 mm downgrade aggregates demonstrated significantly better passability compared to 20 mm downgrade aggregates. Notably, only Case-5(20), involving pure OPC and recycled sand with 20 mm downgrade aggregates, failed to pass the T5 test.

4.2 Strength and Durability Tests Result

4.2.1 Compression Test Result

4.2.1.1 7-Days Result

The strength obtained from 7-Days compression test are shown in **Table 17** below

Table 17 7-Days Compression Test Result

Case no	Details	Mpa
2 (15)	100% RBA + 100% **NS** + OPC + FA + Sl	**15.2**
4 (15)	100% RBA + 100% **NS** + OPC + FA + Sl +SF	**18.7**
3 (15)	100% RBA + 100% **RS** + OPC + FA + Sl +SF	**19.39**
1 (20)	100% RBA + 100% **RS** + OPC + FA + Sl	**23.54**
1 (15)	100% RBA + 100% **RS** + OPC + FA + Sl	**23.8**
3 (20)	100% RBA + 100% **RS** + OPC + FA + Sl +SF	**24.04**
2 (20)	100% RBA + 100% **NS** + OPC + FA + Sl	**27.21**
4 (20)	100% RBA + 100% **NS** + OPC + FA + Sl +SF	**27.66**
5 (15)	100% RBA + 100% **RS** + OPC (500)	**33.5**
5 (20)	100% RBA + 100% **RS** + OPC (500)	**41.34**

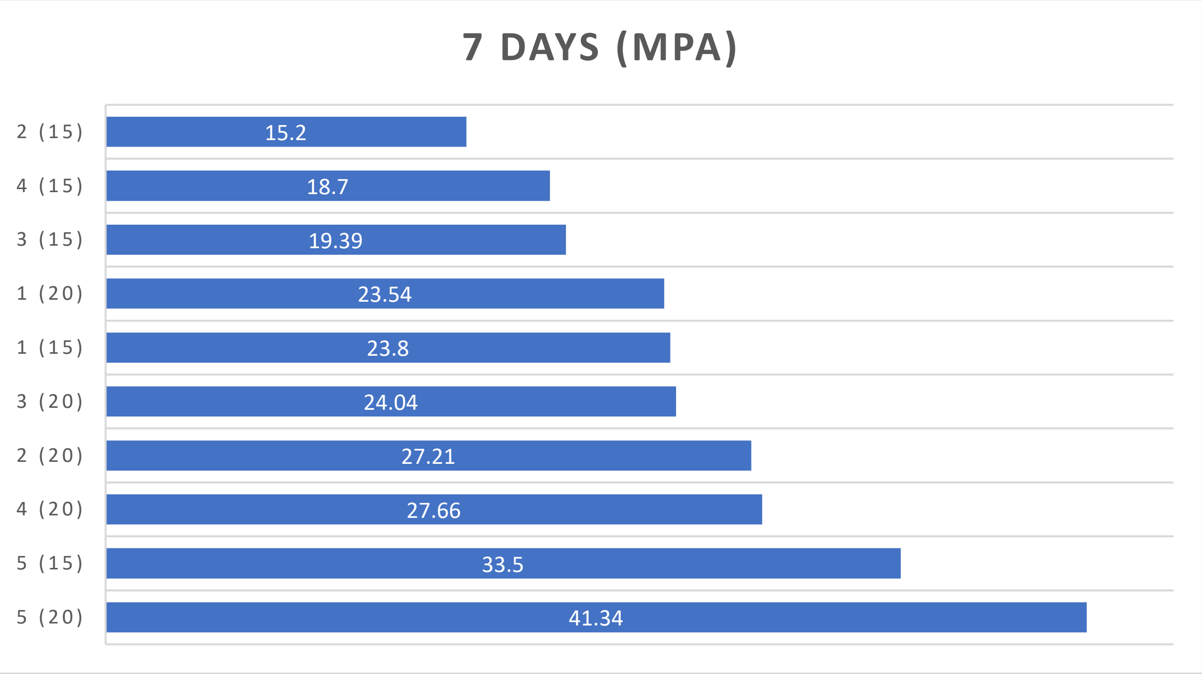

Figure 14 *7-Days Compression Test Result*

4.2.1.2 14-Days Result

The strength obtained from 14-Days compression test are shown in **Table 18** below

Table 18 14-Days Compression Test Result

Case no	Details	Mpa
2 (15)	100% RBA + 100% **NS** + OPC + FA + Sl	**19.9**
4 (15)	100% RBA + 100% **NS** + OPC + FA + Sl +SF	**24.97**
3 (15)	100% RBA + 100% **RS** + OPC + FA + Sl +SF	**25.86**
3 (20)	100% RBA + 100% **RS** + OPC + FA + Sl +SF	**29.17**
1 (15)	100% RBA + 100% **RS** + OPC + FA + Sl	**29.92**
1 (20)	100% RBA + 100% **RS** + OPC + FA + Sl	**30.05**
2 (20)	100% RBA + 100% **NS** + OPC + FA + Sl	**30.12**
4 (20)	100% RBA + 100% **NS** + OPC + FA + Sl +SF	**34.43**
5 (15)	100% RBA + 100% **RS** + OPC (500)	**35.25**
5 (20)	100% RBA + 100% **RS** + OPC (500)	**43.68**

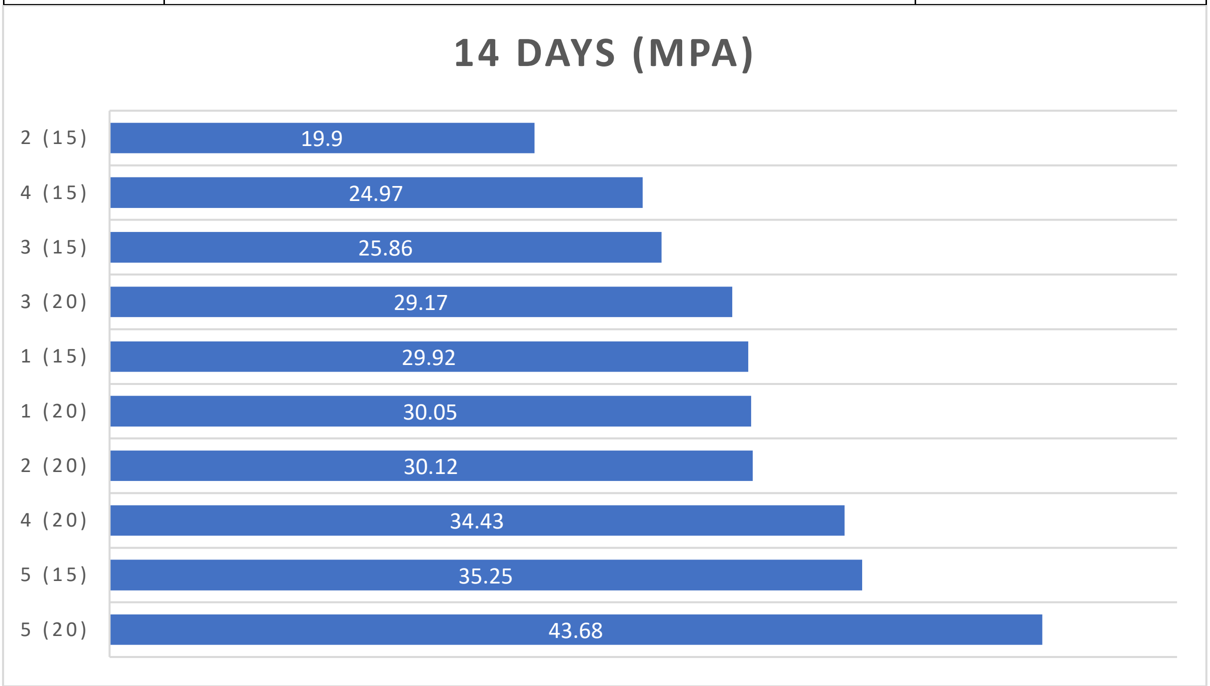

Figure 15 *14-Days Compression Test Result*

4.2.1.3 28-Days Result

The strength obtained from 28-Days compression test are shown in **Table 19** below

Table 19 28-Days Compression Test Result

Case no	Details	Mpa
2 (15)	100% RBA + 100% **NS** + OPC + FA + Sl	**20**
4 (15)	100% RBA + 100% **NS** + OPC + FA + Sl +SF	**25.21**
3 (15)	100% RBA + 100% **RS** + OPC + FA + Sl +SF	**27.7**
3 (20)	100% RBA + 100% **RS** + OPC + FA + Sl +SF	**30.06**
1 (15)	100% RBA + 100% **RS** + OPC + FA + Sl	**31.2**
2 (20)	100% RBA + 100% **NS** + OPC + FA + Sl	**31.4**
1 (20)	100% RBA + 100% **RS** + OPC + FA + Sl	**33.32**
4 (20)	100% RBA + 100% **NS** + OPC + FA + Sl +SF	**35.19**
5 (15)	100% RBA + 100% **RS** + OPC (500)	**35.27**
5 (20)	100% RBA + 100% **RS** + OPC (500)	**44.16**

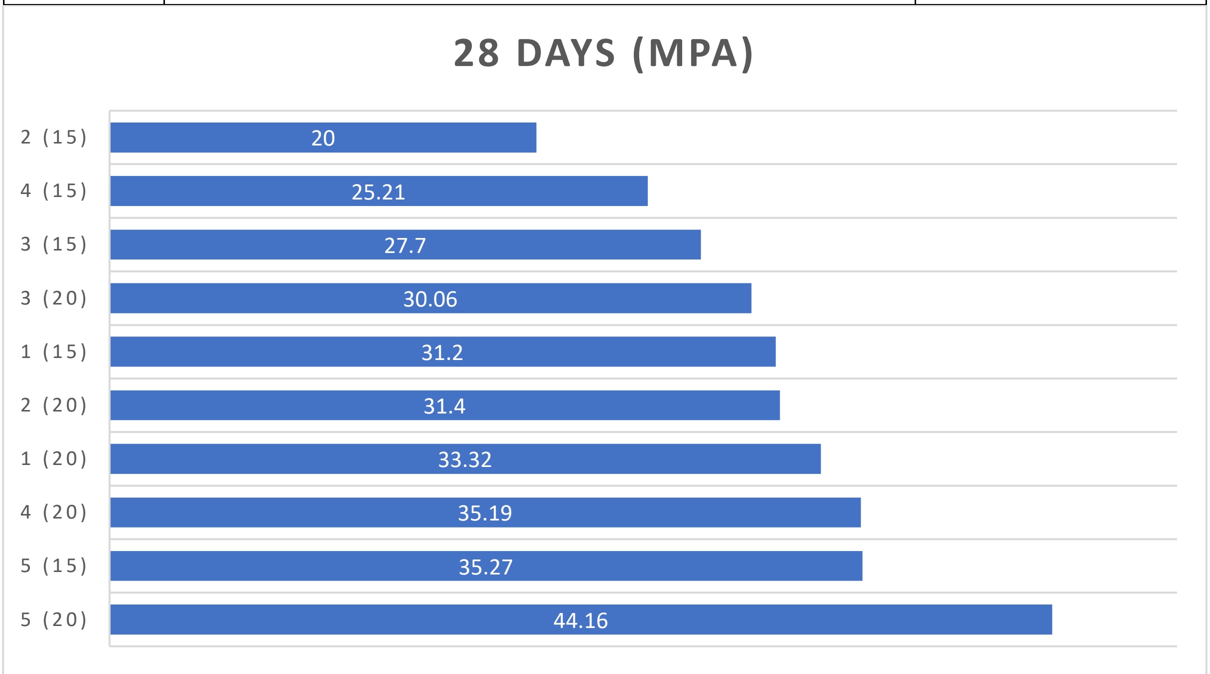

***Figure 16** 28-Days Compression Test Result*

4.2.1.4 90-Days Result

The strength obtained from 90-Days compression test are shown in **Table 20** below

Table 20 90-Days Compression Test Result

Case no	Details	Mpa
4 (15)	100% RBA + 100% NS + OPC + FA + Sl +SF	**28.95**
3 (15)	100% RBA + 100% RS + OPC + FA + Sl +SF	**30.87**
3 (20)	100% RBA + 100% RS + OPC + FA + Sl +SF	**33.45**
2 (15)	100% RBA + 100% NS + OPC + FA + Sl	**35.28**
2 (20)	100% RBA + 100% NS + OPC + FA + Sl	**36.19**
4 (20)	100% RBA + 100% NS + OPC + FA + Sl +SF	**36.42**
1 (20)	100% RBA + 100% RS + OPC + FA + Sl	**39.07**
5 (15)	100% RBA + 100% RS + OPC (500)	**42.92**
1 (15)	100% RBA + 100% RS + OPC + FA + Sl	**43.16**
5 (20)	100% RBA + 100% RS + OPC (500)	**45.83**

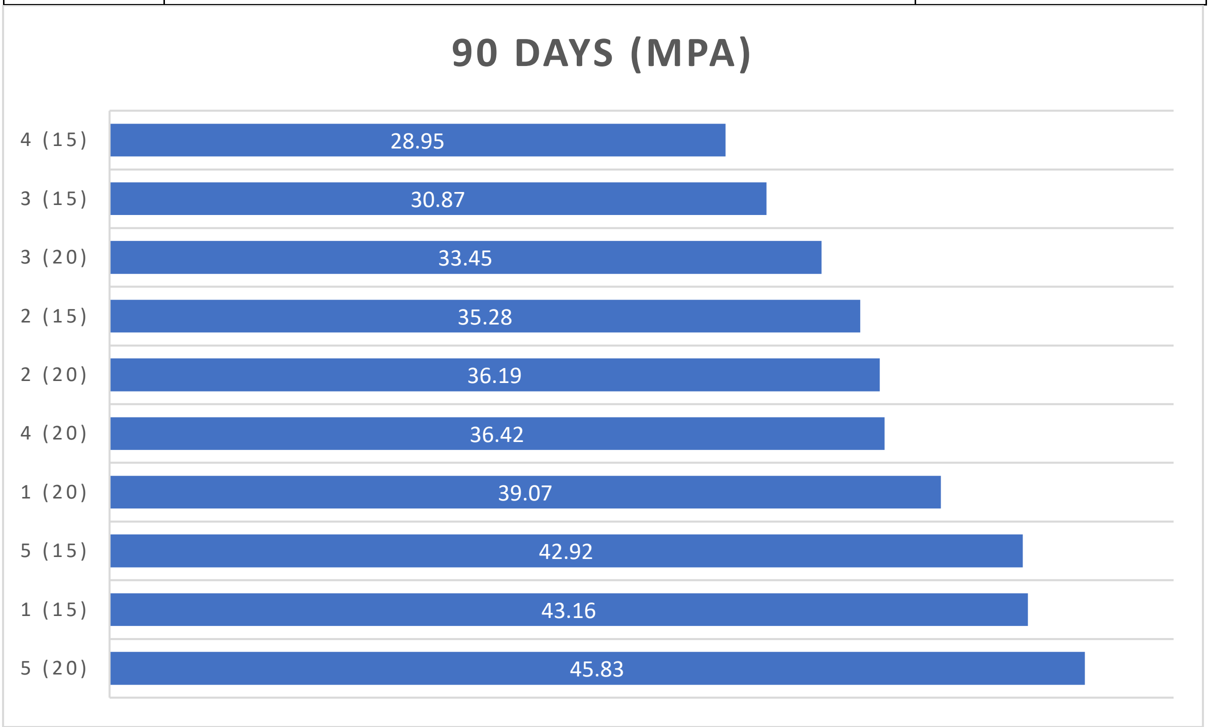

Figure 17 *90-Days Compression Test Result*

4.2.1.5 Compression test result analysis

At 7 days, the compressive strengths ranged from 15.2 MPa to 41.34 MPa, with Case- 5(20) showing the highest strength due to the use of pure OPC (500) and 20 mm downgrade aggregate. The lowest recorded result was from a natural sand Case-2(15) mixed with slag, fly ash and 15 mm downgrade aggregate. The second highest strength was also obtained from the use of pure OPC (500) which is Case-5(15) but with 15 mm downgrade aggregate. By 14 days, the strength values increased, ranging from 19.9 MPa to 43.68 MPa, with Case 5 (20) still exhibiting the highest strength. Case- 1(20), 2(20) and 4 (20) crossed 30 MPa strength. The 28-days results demonstrated further gains in strength, with values spanning from 20 MPa to 44.16 MPa. Finally, at 90 days, the compressive strengths ranged from 28.95 MPa to 45.83 MPa, with the highest strength observed again in Case 5 (20) and lowest strength for Case- 4(15) with natural sand mixed with slag, fly ash and silica fume and 15 mm downgrade aggregate. Cases- 5(15), 1(15) and 5(20) crossed 40 MPa strength. All other cases were within 30-40 MPa strength except for Case- 4(15).

The analysis of the compressive strength test results indicates that using recycled sand as a fine aggregate produced superior strength compared to natural sand. Partial replacement of OPC with slag, fly ash, and silica fume generally resulted in lower strengths, whereas the pure OPC cases exhibited the highest strengths. Additionally, 20 mm downgrade aggregates consistently yielded higher strength compared to the 15 mm downgrade aggregates.

4.2.2 Ultrasonic Pulse Velocity (UPV) Test Result

4.2.2.1 7-Days Result

7-Days Ultrasonic Pulse Velocity (UPV) test results are shown in **Table 21** below

Table 21 7-Days UPV test results

Case no	Details	µs	m/s
1 (15)	100% RBA + 100% RS + OPC + FA + Sl	**61**	**3345**
1 (20)	100% RBA + 100% RS + OPC + FA + Sl	**60.4**	**3361**
2 (15)	100% RBA + 100% NS + OPC + FA + Sl	**57.4**	**3433.1**
2 (20)	100% RBA + 100% NS + OPC + FA + Sl	**49.9**	**4066**
3 (15)	100% RBA + 100% RS + OPC + FA + Sl +SF	**55.6**	**3651**
3 (20)	100% RBA + 100% RS + OPC + FA + Sl +SF	**60.5**	**3353.7**
4 (15)	100% RBA + 100% NS + OPC + FA + Sl +SF	**60.90**	**3333**
4 (20)	100% RBA + 100% NS + OPC + FA + Sl +SF	**51.5**	**3943.7**
5 (15)	100% RBA + 100% RS + OPC (500)	**59.30**	**3411**
5 (20)	100% RBA + 100% RS + OPC (500)	**55.2**	**3653**

4.2.2.2 14-Days Result

14-Days Ultrasonic Pulse Velocity (UPV) test results are shown in **Table 22** below

Table 22 14-Days UPV test results

Case no	Details	µs	m/s
1 (15)	100% RBA + 100% RS + OPC + FA + Sl	**57.8**	**3501**
1 (20)	100% RBA + 100% RS + OPC + FA + Sl	**56.7**	**3578.3**
2 (15)	100% RBA + 100% NS + OPC + FA + Sl	**55.3**	**3671.3**
2 (20)	100% RBA + 100% NS + OPC + FA + Sl	**48.15**	**4216**
3 (15)	100% RBA + 100% RS + OPC + FA + Sl +SF	**52.4**	**3874**
3 (20)	100% RBA + 100% RS + OPC + FA + Sl +SF	**57.7**	**3520.3**
4 (15)	100% RBA + 100% NS + OPC + FA + Sl +SF	**59.90**	**3389.2**
4 (20)	100% RBA + 100% NS + OPC + FA + Sl +SF	**49.7**	**4082**
5 (15)	100% RBA + 100% RS + OPC (500)	**58.20**	**3486.7**
5 (20)	100% RBA + 100% RS + OPC (500)	**54.7**	**3706.7**

4.2.2.3 28-Days Result

28-Days Ultrasonic Pulse Velocity (UPV) test results are shown in **Table 23** below

Table 23 28-Days UPV test results

Case no	Details	µs	m/s
1 (15)	100% RBA + 100% RS + OPC + FA + Sl	**56.4**	**3599**
1 (20)	100% RBA + 100% RS + OPC + FA + Sl	**55.9**	**3631**
2 (15)	100% RBA + 100% NS + OPC + FA + Sl	**53.7**	**3777.67**
2 (20)	100% RBA + 100% NS + OPC + FA + Sl	**50.4**	**4028**
3 (15)	100% RBA + 100% RS + OPC + FA + Sl +SF	**52.1**	**3881.5**
3 (20)	100% RBA + 100% RS + OPC + FA + Sl +SF	**57.6**	**3521.5**
4 (15)	100% RBA + 100% NS + OPC + FA + Sl +SF	**56.40**	**3599**
4 (20)	100% RBA + 100% NS + OPC + FA + Sl +SF	**49.4**	**4109**
5 (15)	100% RBA + 100% RS + OPC (500)	**56.80**	**3574**
5 (20)	100% RBA + 100% RS + OPC (500)	**54.2**	**3745**

4.2.2.4 90-Days Result

90-Days Ultrasonic Pulse Velocity (UPV) test results are shown in **Table 24** below

Table 24 90-Days UPV test results

Case no	Details	µs	m/s
1 (15)	100% RBA + 100% RS + OPC + FA + Sl	**52.9**	**3837**
1 (20)	100% RBA + 100% RS + OPC + FA + Sl	**55.4**	**3664**
2 (15)	100% RBA + 100% NS + OPC + FA + Sl	**49.2**	**4126**
2 (20)	100% RBA + 100% NS + OPC + FA + Sl	**45.9**	**4423**
3 (15)	100% RBA + 100% RS + OPC + FA + Sl +SF	**52.4**	**3874**
3 (20)	100% RBA + 100% RS + OPC + FA + Sl +SF	**56.4**	**3599**
4 (15)	100% RBA + 100% NS + OPC + FA + Sl +SF	**56.4**	**3599**
4 (20)	100% RBA + 100% NS + OPC + FA + Sl +SF	**49.4**	**4109**
5 (15)	100% RBA + 100% RS + OPC (500)	**55.6**	**3651**
5 (20)	100% RBA + 100% RS + OPC (500)	**52.9**	**3837**

4.2.2.5 UPV test result analysis

The Ultrasonic Pulse Velocity (UPV) test results over 7, 14, 28, and 90 days reveal key insights into concrete quality and homogeneity. At 7 days, Case 2-(20) with 20 mm downgrade aggregate and natural sand exhibited the highest velocity of 4066 m/s, indicating superior quality, while Case 4-(15) with 15 mm downgrade aggregate had the lowest at 3333 m/s. By 14 days, velocities increased, with Case 2-(20) reaching 4216 m/s. At 28 days, the trends remained consistent, with Case 2-(20) showing the highest velocity of 4028 m/s. By 90 days, Case 2-(20) again had the highest velocity at 4423 m/s, confirming its superior long-term quality. Overall, natural sand mixes demonstrated higher velocities than recycled sand, and 20 mm aggregates consistently outperformed 15 mm aggregates in terms of concrete quality and homogeneity. Mixes with partial replacements of slag, fly ash, and silica fume generally had lower velocities compared to pure OPC mixes, indicating some reduction in quality.

4.2.3 Rapid Chloride Penetration Test (RCPT) Result

Rapid Chloride Penetration Test (RCPT) results for all 10 cases are shown in **Table 25** below

Table 25 RCPT Result

Case No.	1 (15)	1 (20)	2 (15)	2 (20)	3 (15)	3 (20)	4 (15)	4 (20)	5 (15)	5 (20)
Details	RBA+RS +OPC+F A+Sl	RBA+RS +OPC+F A+Sl	RBA+NS +OPC+F A+Sl	RBA+NS +OPC+F A+Sl	RBA+RS+ OPC+FA +Sl+SF	RBA+RS+ OPC+FA+ Sl+SF	RBA+NS+ OPC+FA+ Sl+SF	RBA+NS+ OPC+FA+ Sl+SF	RBA+RS +OPC (500)	RBA+RS +OPC (500)
Ampere	0.038	0.067	0.069	0.08	0.023	0.015	0.019	0.037	0.146	0.139
	0.044	0.078	0.079	0.09	0.023	0.025	0.018	0.038	0.178	0.18
	0.046	0.085	0.089	0.099	0.023	0.027	0.019	0.038	0.206	0.21
	0.046	0.091	0.098	0.101	0.023	0.028	0.019	0.038	0.222	0.23
	0.046	0.095	0.099	0.102	0.023	0.028	0.019	0.038	0.237	0.244
	0.047	0.095	0.101	0.11	0.023	0.028	0.019	0.039	0.247	0.26
	0.048	0.099	0.109	0.116	0.023	0.028	0.019	0.04	0.255	0.271
	0.05	0.102	0.11	0.117	0.023	0.028	0.02	0.042	0.261	0.281
	0.05	0.103	0.114	0.119	0.023	0.028	0.02	0.043	0.268	0.291
	0.051	0.104	0.117	0.12	0.023	0.028	0.021	0.045	0.278	0.306
	0.052	0.104	0.118	0.121	0.023	0.028	0.021	0.045	0.301	0.33
	0.052	0.102	0.118	0.121	0.023	0.028	0.021	0.045	0.3	0.324
	0.053	0.099	0.119	0.12	0.023	0.028	0.021	0.046	0.294	0.321
Charge Passed=	**1087.2**	**2142.9**	**2349.9**	**2476.8**	**517.5**	**611.1**	**443.7**	**927.9**	**5616**	**5971.5**
Chloride Ion Penetrability=	**Low**	**Moderate**	**Moderate**	**Moderate**	**Very Low**	**Very Low**	**Very Low**	**Very Low**	**High**	**High**

The pure OPC cases (Case 5) with recycled sand for both 15 mm and 20 mm downgrade aggregates exhibited the highest chloride ion penetrability, classified as "High" at 5616 and 5971.5 coulombs respectively. In contrast, mixes with partial replacements of OPC with slag, fly ash, and silica fume generally showed lower chloride ion penetrability. Case-4(15), composed of natural sand and 15 mm downgrade aggregate with fly ash, slag and silica fume, had the lowest classification with 443.7 coulombs. All cases containing silica fume yielded “Very Low” classification in penetrability. The cases with only fly ash and slag and no silica fume generally fell within the range of “Low” to “Moderate” penetrability. The natural sand mixes tended to perform better than recycled sand mixes, and the 15 mm downgrade aggregates generally allowed lower penetration compared to their 20 mm counterparts. This indicates that natural sand compared to recycled sand and smaller aggregate sizes are more capable of decreasing penetrability. Again, mixes with partial OPC replacements containing silica fume can significantly improve resistance to chloride ion penetration.

A summary of the RCPT result obtained is shown in ascending order in terms of penetrability in the **Table 26** below

Table 26 RCPT Result Summary

Case no	Details	Charge Passed	Chloride Ion Penetrability
4 (15)	100% RBA + 100% NS + OPC + FA + Sl +SF	**443.7**	**Very Low**
3 (15)	100% RBA + 100% RS + OPC + FA + Sl +SF	**517.5**	**Very Low**
3 (20)	100% RBA + 100% RS + OPC + FA + Sl +SF	**611.1**	**Very Low**
4 (20)	100% RBA + 100% NS + OPC + FA + Sl +SF	**927.9**	**Very Low**
1 (15)	100% RBA + 100% RS + OPC + FA + Sl	**1087.2**	**Low**
1 (20)	100% RBA + 100% RS + OPC + FA + Sl	**2142.9**	**Moderate**
2 (15)	100% RBA + 100% NS + OPC + FA + Sl	**2349.9**	**Moderate**
2 (20)	100% RBA + 100% NS + OPC + FA + Sl	**2476.8**	**Moderate**
5 (15)	100% RBA + 100% RS + OPC (500)	**5616**	**High**
5 (20)	100% RBA + 100% RS + OPC (500)	**5971.5**	**High**

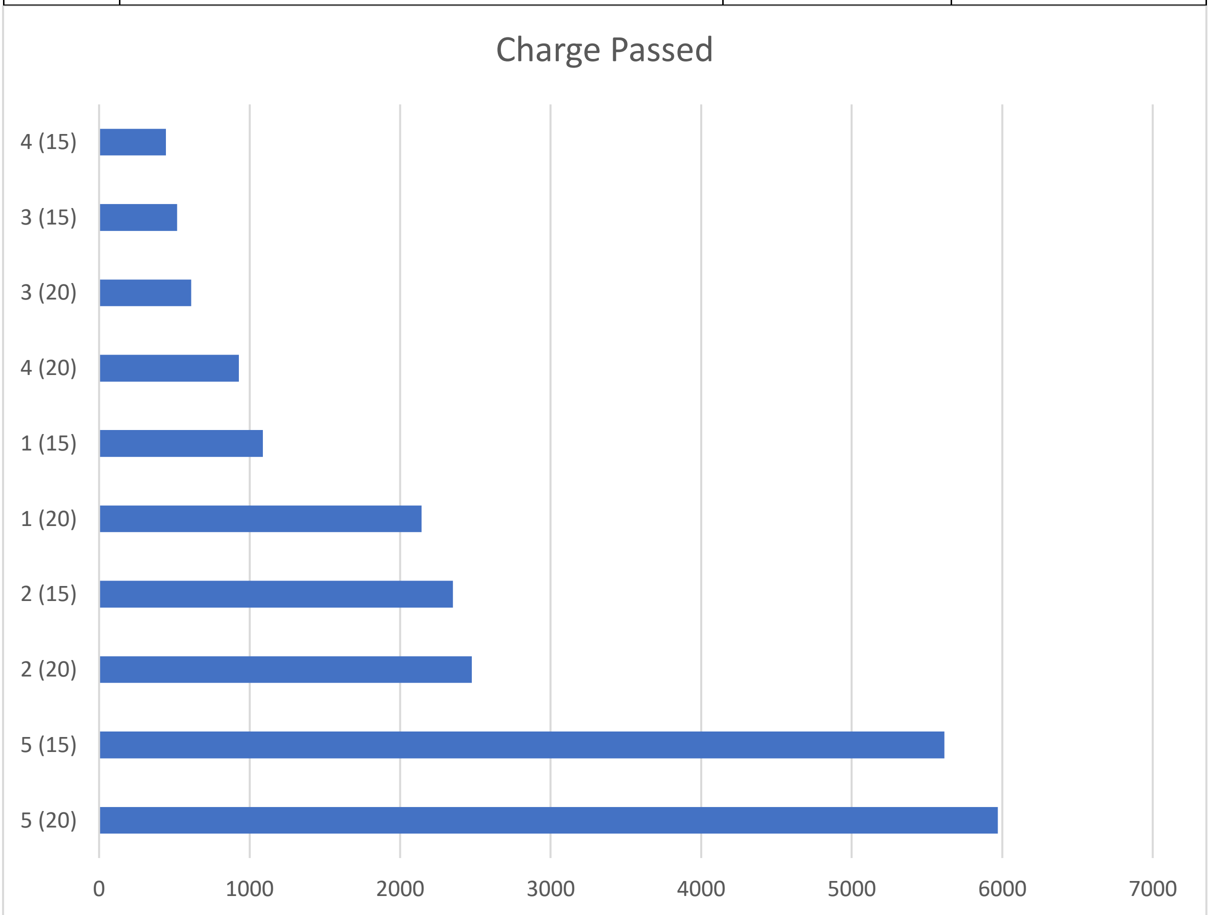

***Figure 18** RCPT Result Summary*

4.2.4 Scanning Electron Microscopy (SEM) Result

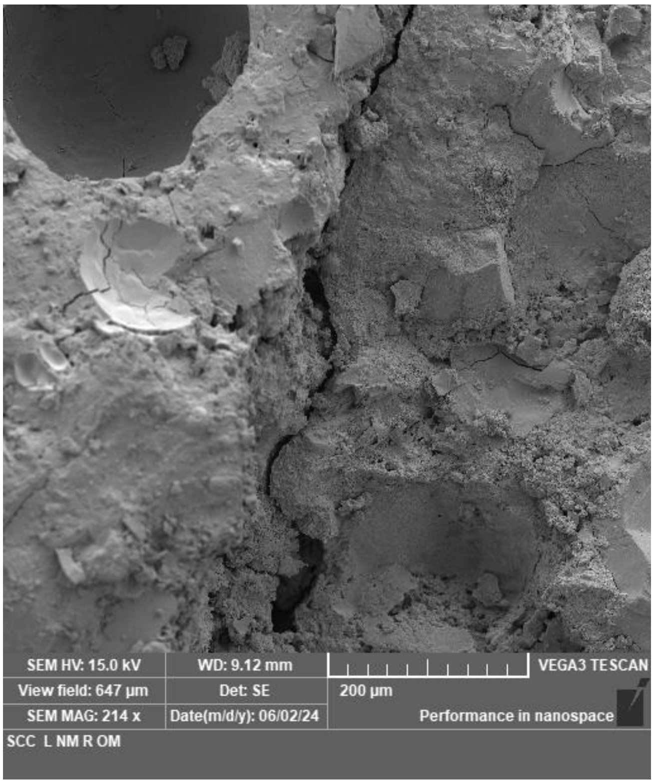

Figure 19 *SEM Result 1*

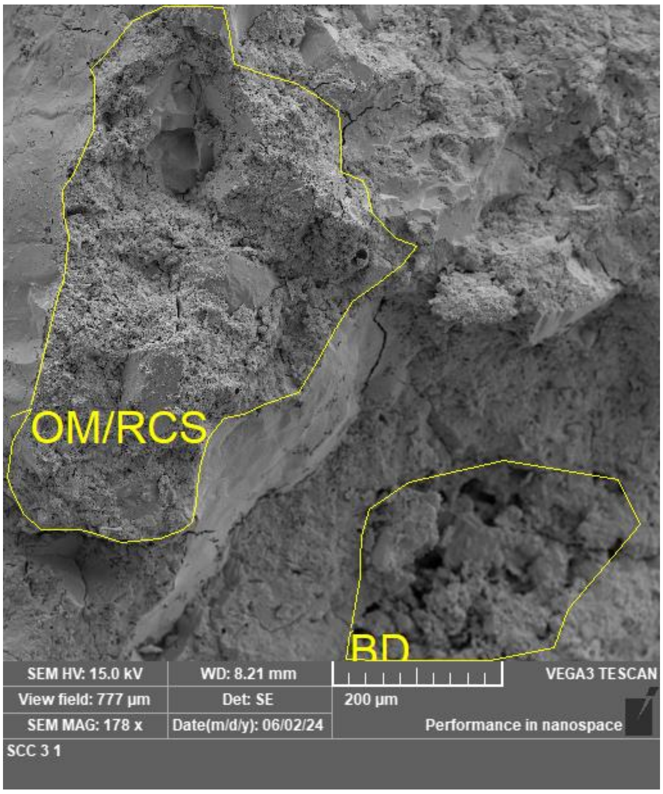

Figure 20 *SEM Result 2*

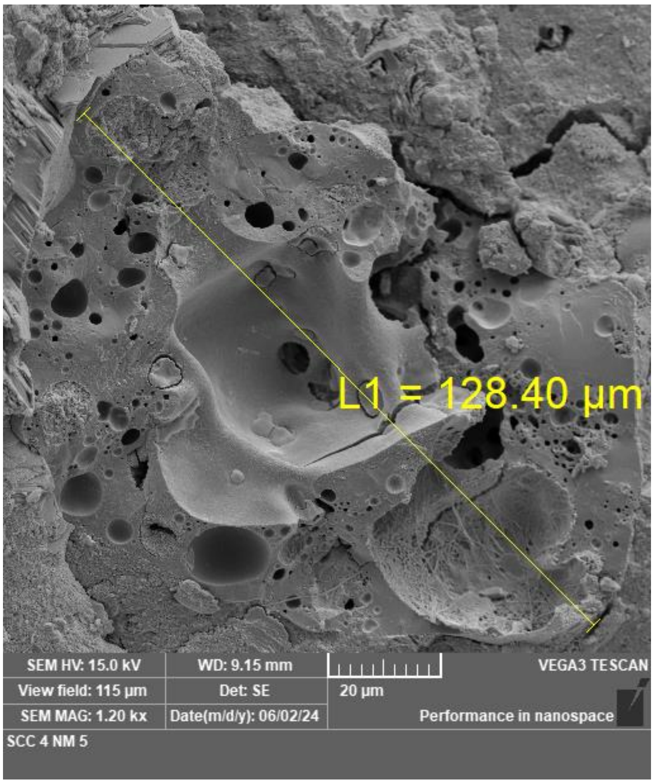

Figure 21 *SEM Result 3*

Chapter 5: Conclusion and Recommendation

5.1 General

The primary objective of this study was to determine the possibility of producing self-compacting concrete (SCC) using recycled brick aggregate. This chapter describes the summary of the research findings based on the results and discussions in Chapter 4. Moreover, the conclusion and recommendations for this investigation are also mentioned in this chapter.

5.2 Conclusion

According to the study's experimental findings, it can be ensured that it is possible to produce self-compacting concrete (SCC) with recycled brick using the right design mix.

In case of using natural sand as fine aggregate the overall best results were obtained from Case-2 (15) which consisted of fly ash and slag using 15 mm downgrade aggregates. The flow result came at 667.5 mm diameter with 657.5 mm diameter in case of J-ring test which is within the 500-700 mm diameter mark easily. The immediate V-funnel time was at 6.9 seconds and T5 time was at 7.5 seconds which both were the fastest among all cases and it satisfies the 6-12 second criteria. The 90-days ultimate strength was obtained at 35.28 MPa. The RCPT result was within the "Moderate" classification for penetration.

In case of using recycled sand as fine aggregate the best performing case overall was Case-1(15) which also consisted of fly ash and slag only using 15 mm downgrade aggregates. The flow result came at 687.5 mm diameter with 520 mm diameter in case of J-ring test which both satisfy the 500-700 mm diameter requirement. The immediate V-funnel time was at 9.6 seconds and T5 time was at 10.3 seconds which both satisfies the 6-12 second criteria and is the second fastest among all cases. The 90-days ultimate strength was obtained at 43.16 MPa which is the second highest strength obtained. The RCPT result was within the "Low" classification for penetration.

Overall best results obtained from cases which utilized silica fume along fly ash and slag was Case-4 (20) using natural sand and 20 mm downgrade aggregate. This case had a Flow and J-ring diameter of 625 mm and 550 mm respectively which satisfy the 500-700 mm criteria. The V-funnel test result yielded T0 and T5 time of 13 and 14.3 seconds which are close enough to the 6-12 second criteria. The 90-days ultimate strength was obtained at 36.42 MPa. The RCPT result was within the "Very Low" classification and had the second lowest penetration.

Overall best results obtained from cases which utilized pure OPC mix was Case-5 (15) using recycled sand and 15 mm downgrade aggregate. This case had a Flow and J-ring diameter of 677.5 mm and 510 mm respectively which satisfy the 500-700 mm criteria. The V-funnel test result yielded T0 and T5 time of 10 and 12.45 seconds which also narrowly satisfies the 6-12 second criteria. The 90-days ultimate strength was obtained at 42.92 MPa which was the third highest. The RCPT result was within the "High" classification which couldn't be satisfactory having the second highest penetration.

The worst result was obtained from Case-5(20) which was a pure OPC mix with recycled sand and 20 mm downgrade aggregate. It had the lowest flow result at 535 mm diameter and failed the J-ring and V-funnel T5 tests. It had the 90-days ultimate strength at 45.83 MPa. The RCPT result was within the "High" classification and had the highest penetration.

5.3 Recommendation

Recycled sand as a fine aggregate had a tendency of setting significantly faster than natural sand mix. The fresh tests need to be conducted very fast or else the results will be drastically impacted. It is better to use fresh batches of concrete mix for different fresh tests rather than reusing the concrete mix from the previously conducted test. Silica Fume can significantly reduce bleeding but it also reduces flow property. Higher admixture doses are more required for recycled sand and silica fume cases. 15 mm downgrade aggregate is much better for producing self-compacting concrete (SCC) using recycled sand as fine aggregate. In case of producing SCC with 20 mm downgrade aggregates natural sand as fine aggregate yield much better results.

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