Selected Fresh and Hardened Self Compacting Concrete Incorporating PP Macro Fibers, Crushed Brick Aggregate, and Fly Ash

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ABSTRACT

The increasing demand for high-performance concrete that can flow and compact itself without the aid of mechanical compaction has driven the development of more efficient and sustainable Self-Compacting Concrete (SCC). The novelty of this study lies in the comprehensive evaluation of SCC incorporating a unique combination of Crushed Brick Aggregate (CBA), Polypropylene (PP) macro fibers, and varying Fly Ash (FA) content, which has not been extensively explored in previous studies. Unlike conventional SCC studies, this work systematically investigated the influence of different FA replacement levels on both the fresh and mechanical properties of an SCC mix containing CBA, a material known for its high water absorption and lower strength compared to natural aggregates. The findings provide critical insights into optimizing FA content to enhance SCC workability while mitigating the potential strength reduction associated with excessive cement substitution and CBA's physical characteristics. The results show that the addition of FA increased the slump flow, decreased the V-funnel flow time, and increased the L-box blocking ratio, with the best results having been achieved with 30% and 40% FA content. In addition, at 20% FA content, there was a significant increase in compressive strength, flexural strength, and elastic modulus compared to the control sample without FA. This study demonstrates that FA at a content of 20% yielded the best results in improving SCC performance both in fresh and hardened conditions, whereas a higher FA content decreases the mechanical properties of concrete.

Keywords-self-compacting concrete; polypropylene macro fiber; crushed brick aggregate; fly ash; workability; mechanical strength

I. INTRODUCTION

High-performance concrete materials that may increase structural quality and work efficiency are becoming more and more essential in modern building construction. One novel approach is the SCC, which can flow and compact itself without the use of mechanical compaction tools [1]. SCC also offers a more homogeneous finish and high strength, making it a superior choice for a variety of construction applications. However, SCC has drawbacks related to its weight and flexural strength that must be considered [2].

SCC is heavier than ordinary concrete because it contains more components, such as fillers and fine particles, to attain excellent flow qualities, making it less suited for applications requiring lightweight buildings. Furthermore, the flexural strength of SCC is relatively low because the large amount of fine aggregate limits the interlocking between coarse aggregate particles, which is critical for resisting tensile or flexural stress. However, these drawbacks may be mitigated by good mix design, such as the use of lightweight aggregates to reduce weight and the use of macro fibers (such as PP) to improve flexural strength [3, 4].

One way to minimize the weight of concrete is to utilize lighter aggregates, [5] such as CBA. CBA in concrete has several advantages, including decreasing building waste by using recycled materials and lowering the environmental effects of mining natural aggregates. CBA is lighter than standard aggregates, reducing the weight of concrete constructions, which is advantageous for situations requiring low loads [6]. In addition, CBA has greater porosity. CBA can improve the flow and compaction in SCC, but maximum performance requires careful monitoring of the material quality and balance. Its use can help lower the cost of concrete manufacturing, particularly when replacing the increasingly expensive natural aggregates.

Furthermore, adding fibers in concrete has been shown to improve its mechanical properties [7]. PP macro fibers exhibit improved flexural strength and fracture resistance and can be used in SCC [8]. Furthermore, PP macro fibers increase the resistance of concrete to impact and deformation caused by dynamic loads, hence increasing its service life. Their lightweight and non-absorbent nature also prevents moisture from degrading concrete performance in SCC.

In addition to fibers, FA in SCC has been shown to greatly increase concrete performance due to its particular characteristics [9]. FA, a pozzolanic material, is combined with the calcium hydroxide generated during cement hydration to form calcium silicate hydrate (C-S-H), increasing concrete strength. Furthermore, the tiny particles of FA improve workability by filling the spaces between the aggregate particles, resulting in a more homogenous mixture and easier flow [10]. FA also improves the durability of concrete by decreasing its porosity and permeability, making it more resistant to chemical attacks from sulfates and chlorides. With these advantages, FA as a cement alternative not only addresses SCC limitations, but also promotes sustainability by utilizing industrial waste to minimize CO_2 emissions from Portland cement manufacturing operations.

Previous studies on SCC incorporating CBA have not yet explored the performance of PP macro fibers in mixtures with varying FA content. This study addresses this gap by evaluating the combined effects of CBA, PP fibers, and different FA percentages on the properties of fresh and hardened SCC. The conclusions of this study are related to the unique combination of these components to enhance the flow, compaction, and resistance of concrete to compressive and flexural stress. CBA offers an eco-friendly lightweight aggregate option, whereas FA serves as a binder that can reduce the amount of Portland cement in the mixture. This work presents a novel contribution for enhancing SCC performance, promoting sustainability and efficiency, while addressing the issues associated with the utilization of waste materials and improving concrete durability.

II. MATERIALS AND METHODS

A. Cement, Fly Ash and Admixture

The cement utilized for the fabrication of the SCC samples was composite Portland cement, manufactured by PT Semen Jakarta, which satisfies the SNI 7064:2014 standard [11]. The Class F FA was acquired from the Paiton power plant, which fulfills ASTM C 618 [12]. Table I shows the composition of the FA derived from XRF data obtained at the LIPI Serpong laboratory in Indonesia. The additive utilized was Sika ViscoCrete 3115N, which is manufactured from an aqueous solution of modified polycarboxylate copolymers. Figures 1a and 1b depict the cement and FA, respectively. Cement was replaced with 0%, 20%, 30%, and 40% FA by weight, allowing for a comprehensive evaluation of their effects on the properties of both fresh and hardened SCC mixes. According to ASTM C618, the optimal FA content for normal concrete is typically between 15% and 35%. However, in this study, the FA content was extended to 40% to explore its potential benefits in SCC containing CBA and PP fibers. The reasoning behind this is that the inclusion of CBA, with its unique physical properties, and the addition of PP fibers may influence the material's behavior in ways that could accommodate higher FA levels without significantly compromising mechanical performance. Testing up to 40% FA allowed for a comprehensive evaluation of the performance across a broader range of mix designs.

Fig. 1. a) Portland cement and b) FA from the Paiton power plant.

TABLE I. OXIDE CONTENT OF FA

Oxide	Content (%)
SiO_2	63.15
Al_2O_3	16.88
Fe_2O_3	9.23
CaO	4.49
MgO	1.93
TiO_2	1.04
K_2O	0.68
P_2O_5	0.56
Na_2O	0.44
MnO_2	0.32
SO_3	0.1

B. Aggregate, Polypropylene fibers, and Water

Natural river sand with a size of less than 4.75 mm was used to produce fine aggregates. CBA, functioning as a coarse aggregate, was derived from the demolition of surplus bricks or building rubble, available in sizes of 19 and 10 mm. Table II summarizes the physical parameters of the fine aggregates and the CBA [13]. The water used was pure and devoid of dirt, oil, chemicals, and organic compounds.

TABLE II. PROPERTIES OF CBA AND FINE AGGREGATE [13]

Physical properties	Fine aggregate	CBA
Fineness modulus	2.46	5.9
Particle size (mm)	19-4.75	10-19
Absorption (%)	2.3	5.6
Specific gravity	2.76	2.13

CBA has significant porosity, with a water absorption capacity of 5.6%, influencing the water demand in the concrete formulation. CBA, which possesses inferior strength compared to natural aggregates, provides effective thermal insulation and promotes ecologically sustainable concrete through the use of construction waste. However, it necessitates enhanced control in the mix design to address the elevated water absorption. Kratos Macro Fibers were added to the SCC. This comprises a type of PP fibers approximately 40-60 mm in length and 0.9 mm in diameter, including a unique form with locked ends to enhance adhesion to the concrete matrix. The fibers have tensile strength above 600 MPa and an elastic modulus of around 5 GPa, enabling them to endure substantial tensile stresses. These fibers are engineered for durability in demanding settings; they are noncorrosive, lightweight, and chemically stable, guaranteeing sustained performance in concrete. The visual characteristics of the CBA and PP fibers are illustrated in Figures 2a and 2b, respectively.

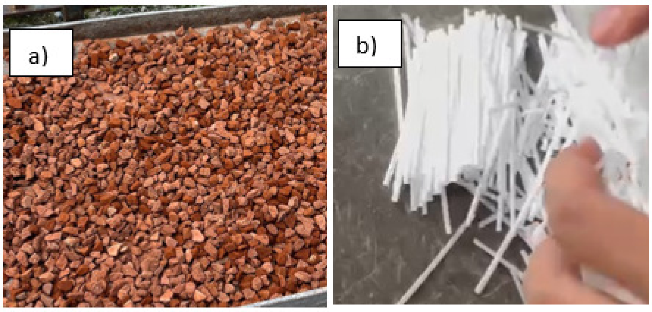

Fig. 2. a) CBA and b) PP macro fibers.

The PP plastic granules used as a substitute for sand were added at three different levels, namely 0, 10%, 20%, and 30% of the sand volume. The plasticizer was added to the mixture at a concentration of 1.5% relative to the cement weight. Table III portrays the sample mix design.

C. Mix Proportion

This study utilized SCC samples incorporating CBA and PP fibers, with FA percentages varying at 0%, 20%, 30%, and 40% relative to cement weight. This concrete was formulated with a packing factor of 1.12 and a water-cement ratio of 0.4. To guarantee a seamless flow and ideal density, 1.2% Sika Viscocrete was used relative to the original weight of the cement. The PP fiber percentage was established at 0.3% of the concrete volume to enhance the toughness and post-cracking strength. The mix design employed was based on the method introduced in [14], which considered parameters, such as FA concentration, aggregate type, and additives to obtain the desired concrete performance. The specific mixture proportions are listed in Table III.

TABLE III. MIX PROPORTION OF SAMPLE

Sample ID	Cement (kg/m^3)	FA (kg/m^3)	Fine aggregate (kg/m^3)	CBA (kg/m^3)	Water (kg/m^3)	PP fibers (kg/m^3)	Admixture (kg/m^3)	w/c ratio
CBA-FA0%	450	-	800.31	235.2	180	2.7	5.4	0.4
CBA-FA20%	360	90	800.31	235.2	180	2.7	5.4	0.4
CBA-FA30%	315	135	800.31	235.2	180	2.7	5.4	0.4
CBA-FA40%	270	180	800.31	235.2	180	2.7	5.4	0.4

D. Testing Procedure

The testing of SCC samples included the assessment of the quality of fresh SCC in accordance with "The European Guidelines for Self-Compacting Concrete 2005" [15], and the examination of the mechanical characteristics following the ASTM standards. For estimating the fresh properties, the slump flow test (550–850 mm), L-box test (0.8-1), and V-funnel test (8–25 seconds) were conducted to assess the flowability, passing ability, and stability of SCC. Compressive strength measurements were performed according to ASTM C39 [16], which utilizes cylindrical specimens to determine compressive strength. The flexural strength was evaluated in accordance with ASTM C78 [17], using concrete blocks with dimensions of 150 mm × 150 mm × 600 mm. The modulus of elasticity was determined according to ASTM C469 [18].

III. RESULTS AND DISCUSSION

A. Density

Figure 3 shows the effect of FA on the density of the SCC-CBA samples utilizing PP fibers. FA influences the density of concrete through two primary mechanisms: direct and indirect. The direct mechanism is based on the fact that FA possesses a lower bulk density than Portland cement; hence, at high replacement levels (>20%), the bulk density of concrete is likely to diminish. Indirectly, FA enhances the microstructural density of concrete by filling the micro-gaps between particles and engaging in pozzolanic reactions with calcium hydroxide ($Ca(OH)_2$), resulting in the formation of calcium silicate hydrate (C-S-H) gel. This procedure decreased the concrete porosity, increased the microstructural density, and reduced the permeability, particularly at an FA replacement rate of 20%, as depicted in Figure 3.

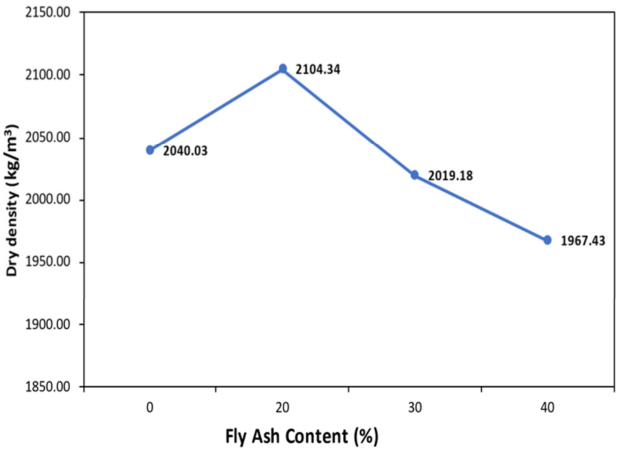

Fig. 3. Dry density of the SCC samples with varying FA content.

B. *Slump Flow, Viscosity, and Flowability*

The slump flow value describes the flowability of SCC. The results presented in Figure 4 indicate that the slump flow value of the SCC samples increases significantly with higher FA content. The slump flow value of the SCC without FA was 62 cm. However, when 20% FA was used, the slump flow value increased to 65 cm, an increase of 4.8 %. The use of 30% FA resulted in a 6.9% increase in slump flow compared to the control sample. The incorporation of 40% FA resulted in a maximum increase in the slump flow of 10.8%, relative to the SCC without FA. This percentage increase indicates that FA played a substantial role in enhancing the workability of SCC, despite the presence of PP and CBA fibers. The pozzolanic properties of FA enhanced particle dispersion in the concrete matrix, thereby improving the fluidity of the mixture.

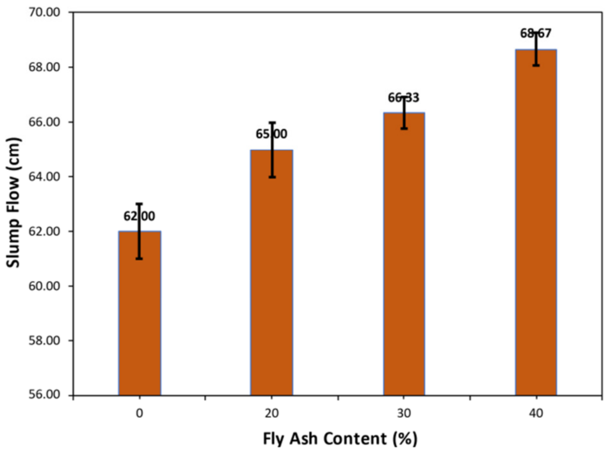

Fig. 4. Slump flow of the SCC samples with varying FA content.

The V funnel tests were performed to assess the viscosity and fluidity of SCC. Figure 5 shows the effect of FA addition on the flow time of the samples. The test results indicate that, as the FA content in the SCC mixture increases, the V-funnel flow time decreases. The flow time in the SCC without FA was measured at 15 s. The incorporation of 20% FA resulted in a flow time reduction to 12.67 s (15.5% decrease). At an FA content of 30%, the flow time was further reduced to 10.33 s, reflecting a decrease of 31.1% compared to the control sample. FA incorporation at levels up to 40% led to the fastest flow time of 9.67 s, representing a reduction of 35.5% compared to the control sample. The reduction in flow time suggests that FA played a crucial role in enhancing the fluidity of the SCC mixture containing CBA and PP fibers.

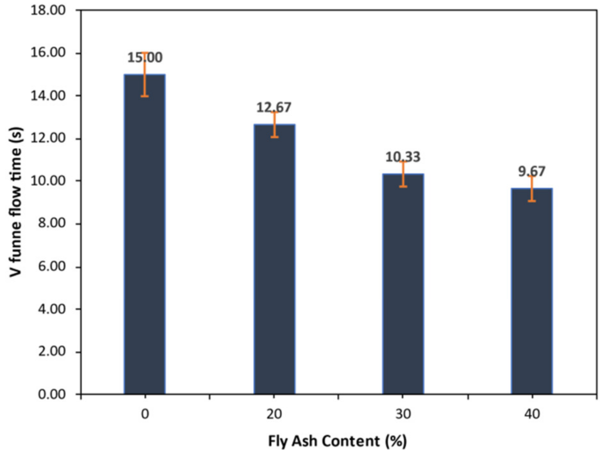

Fig. 5. V funnel flow time of SCC samples with varying FA.

The L-box tests were carried out to estimate the passing capability of the samples. Blocking ratio values approaching 1 indicate that the concrete can traverse the gap with minimal resistance. Figure 6 shows the influence of FA on the blocking ratio of the samples. The test results indicate that the blocking ratio increased with an increasing FA content. The blocking ratio of SCC without FA was 0.8. The inclusion of 20% FA resulted in a 12.5% increase in blocking ratio. The incorporation of 40% FA yielded the maximum blocking ratio value of 0.94. The rise in the blocking ratio value suggests that FA enhances the capacity of concrete to navigate through spaces and around barriers without segregation. The spherical physical properties of FA serve as a lubricant between aggregate particles, whereas its pozzolanic characteristics contribute to a more uniform particle distribution in the concrete mixture [19].

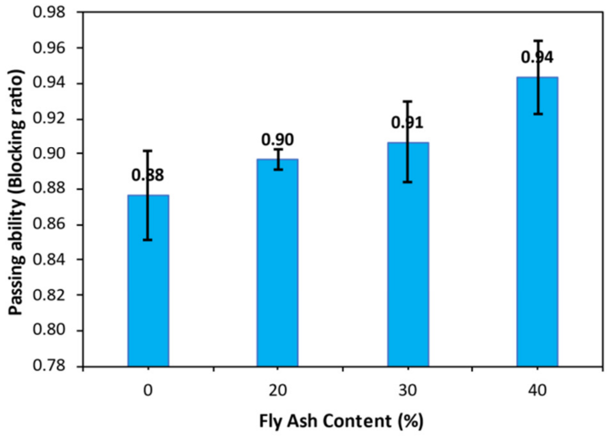

Fig. 6. Passing ability of the SCC samples with varying FA content.

C. Compressive and Flexural Strength

The results of the compressive strength tests for the 7- and 28-day samples are illustrated in Figure 7a. The findings indicate that the compressive strength of SCC incorporating CBA and PP fibers improved with 20% FA content but exhibited a significant decrease at high levels of FA (30% and 40%). At 7 days, the compressive strength of SCC without FA was measured at 18.62 MPa but increased by 7% to 19.92 MPa with the addition of 20% FA. However, a significant decrease of 20.9% and 39.5% at 30% and 40% FA content was observed, respectively. At 28 days, a comparable pattern was observed. The compressive strength rose from 28.56 MPa at 0% FA to 30.32 MPa (6.2% higher) at 20% FA. However, the compressive strength decreased by 21.2% and 34.8% at 30% and 40% FA content, respectively. This comparison indicates that SCC incorporating FA exhibited a more pronounced strength development from 7 days to 28 days at a low content of 20%. However, at higher content levels, the ultimate strength decreased owing to the extended pozzolanic reaction of FA and the physical characteristics of CBA, which restricted the strength of the concrete matrix. Previous research has shown that incorporating 20–30% FA generally enhances the compressive strength, which is attributed to the pozzolanic reaction between FA and calcium hydroxide, leading to a denser microstructure [19]. This observation aligns with the results of the present study, in which the addition of 20% FA demonstrated a notable improvement in compressive strength. Nevertheless, as highlighted in [20], a higher FA content of 30–40% leads to a reduction in compressive strength, which can be attributed to excessive cement replacement and the lower reactivity of FA at higher dosages. The current study's findings confirm this trend, showing that 40% FA resulted in a decline in the mechanical properties of SCC. Although its mechanical behavior was relatively consistent with previous studies, there was a significant strength gap compared to SCC without CBA. In earlier studies, SCC without CBA achieved compressive strengths exceeding 40 MPa, whereas SCC with CBA in the present study reached a maximum strength of only 30.32 MPa.

The findings from the 28-day flexural strength tests of SCC incorporating CBA and PP fibers are portrayed in Figure 7b. The flexural strength of the 20% FA sample was observed to increase by 11.7% in comparison to the control sample. However, a significant reduction in flexural strength at 30% and 40% FA content was observed, measuring 4.56 MPa (a decrease of 47.3%) and 2.79 MPa (a decrease of 67.7%), respectively. In contrast to the 28-day compressive strength results, which indicated an increase at 20% FA but a decline at 30% and 40% (22.52 MPa and 18.62 MPa), it was demonstrated that the incorporation of FA at 20% not only enhanced the compressive strength, but also improved the flexural strength. The observed reduction with higher FA content highlights the vulnerability of flexural strength to the microstructural imperfections within concrete, particularly in the aggregate-matrix transition zone. This issue increases by the physical characteristics of CBA and the significant replacement of cement with FA [21].

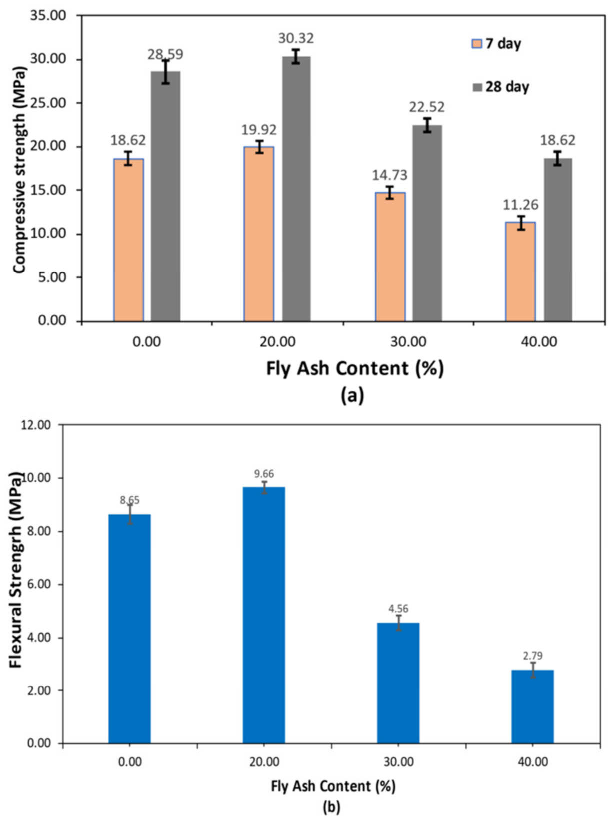

Fig. 7. (a) Compressive and (b) flexural strength of the SCC samples with varying FA content.

D. Elastic Modulus

The findings from the 28-day modulus of elasticity test for SCC incorporating CBA and PP fibers are shown in Figure 8. The observed pattern corresponds closely with the trend in compressive strength, exhibiting an increase at 20% FA content, followed by a significant decrease at higher levels of 30% and 40%. The modulus of elasticity for SCC without FA was 27139.27 MPa, increasing by 6.8% (28984.75 MPa) when incorporating 20% FA. At 30% and 40% FA content, the modulus of elasticity decreased to 22305.1 MPa and 20283.21 MPa, reflecting a reduction of 17.8% and 25.2%, respectively, compared to the control sample.

The reduction observed at high FA levels indicates the negative effect of excessive cement substitution on the strength of the concrete matrix. The reduced mechanical properties of CBA compared to natural aggregates further restrict the capacity of SCC to maintain the modulus of elasticity when a high FA content is used. The data suggest that an FA content of 20% is ideal for achieving a balance between the compressive strength and modulus of elasticity in SCC utilizing CBA and PP fibers.

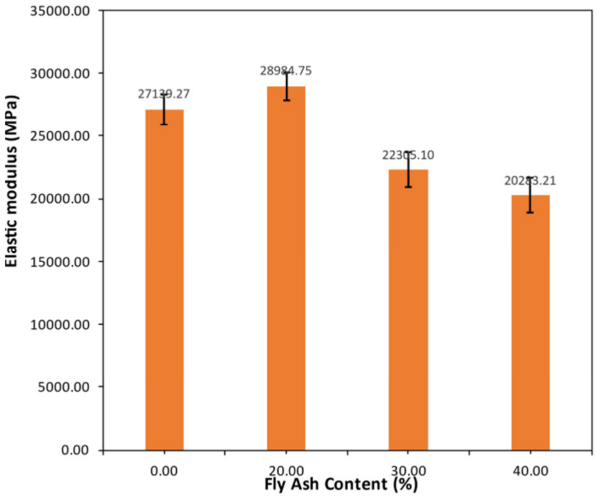

Fig. 8. Elastic modulus of the SCC samples with varying FA content.

E. Testing Process Visualization

The testing of the fresh properties of SCC samples was conducted, as shown in Figure 9, and included flowability i.e. the ability to pass through obstacles, and segregation. The tests met the EFNARC guidelines to ensure an optimal fresh concrete performance [15]. Although, the mechanical properties, such as compressive strength, flexural strength, and elastic modulus describe the strength and deformation of concrete in hardened conditions, the results of the two tests described in this section provide a comprehensive picture of the quality and performance of SCC in structural applications, as illustrated in Figure 10.

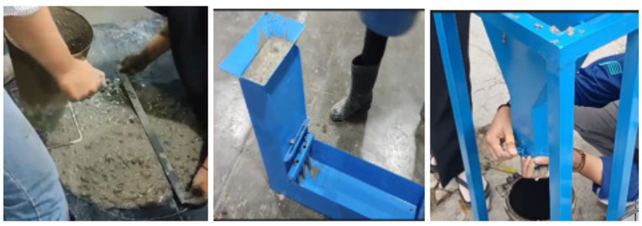

Fig. 9. Test processes for the estimation of the SCC fresh properties.

Fig. 10. Mechanical property test process.

IV. CONCLUSIONS

This study examined how varying Fly Ash (FA) content influenced the mechanical properties of Self-Compacting Concrete (SCC), which incorporated Crushed Brick Aggregate (CBA) and Polypropylene (PP) fibers. The analysis of the test results led to the following conclusions:

- Incorporating FA enhanced the slump flow, decreased the V-funnel flow time, and improved the L-box blocking ratio. The best results were observed at FA contents of 30 and 40%. This FA content enhanced the flowability and passing ability of the SCC.
- Incorporating 20% FA into SCC improved compressive strength, flexural strength, and elastic modulus. This content demonstrated a notable improvement in mechanical performance compared to the control sample that had no FA. Thus, the optimum FA content is 20%.
- With FA contents of 30% and 40%, a significant decrease occurred in all parameters (compressive strength, flexural strength, and elastic modulus), which can be attributed to the adverse impacts of excessive cement replacement and the physical characteristics of CBA.

In addition to the observed improvements in the fresh and hardened properties, the combination of CBA, PP macro fibers, and varying FA contents demonstrates its potential for practical applications in sustainable construction. The proposed SCC can be effectively utilized in non-primary load-bearing structural components, particularly in flexural elements, such as slabs, where its reduced self-weight offers significant advantages. Furthermore, the incorporation of CBA promotes the reutilization of brick waste, contributing to environmental sustainability by reducing construction waste and supporting the development of eco-friendly building materials. The present study highlights the unique combination of CBA, PP macro fibers, and varying FA contents, which have not been extensively explored in previous research. This study systematically investigated the influence of FA replacement levels on the fresh and mechanical properties of SCC, providing critical insights into optimizing the FA content to balance workability and strength.

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