ANALES de Edificación

Received: 20/04/2025
Accepted:28/05/2025

Anales de Edificación
Vol. 11, Nº2, 20-28 (2025)
ISSN: 2444-1309
DOI: 10.20868/ade.2025.5564

Hormigón autocompactante con cenizas volantes
Self-compacting concrete with fly ash

Claudia Delle Cave

PhD candidate at Universidad Politécnica de Madrid.

Resumen-- **El hormigón autocompactante (SCC) es un tipo de hormigón con una elevada capacidad de fluidez, capaz de fluir por efecto de la sola fuerza gravitatoria, sin necesidad de vibración. El SCC en estado fresco tiene características como: alta fluidez y deformabilidad, capacidad de llenado del encofrado por el solo efecto de la fuerza gravitatoria (capacidad de llenado), capacidad de inserción entre armaduras (capacidad de paso), estabilidad (estabilidad), es decir, capacidad del hormigón de permanecer homogéneo, resistencia a la segregación. Las propiedades en estado fresco pueden estimarse realizando ensayos de trabajabilidad como Slump Flow, L-Box, V- Funnel, U-Box, J-Ring. Después del curado, el hormigón autocompactante poseerá las siguientes propiedades: alta resistencia mecánica, durabilidad. La introducción de material ultrafino es la verdadera innovación porque tiende a crear una mezcla compuesta principalmente por partículas diminutas, capaces de transportar áridos gruesos. Se ha observado que las cenizas volantes, cuando se utilizan correctamente, mejoran las propiedades del hormigón tanto en estado fresco como endurecido.**

Palabras clave— Hormigón autocompactante; SCC; propiedades en fresco; propiedades mecánicas; cenizas volantes.

Abstract— **Self-compacting concrete (SCC) is a type of concrete with a high flow capacity, capable of flowing by the effect of gravitational force alone, without the need for vibration. The SCC in its fresh state has characteristics such as: high fluidity and deformability, formwork filling capacity by the sole effect of gravitational force (filling capacity), insertion capacity between reinforcements (passage capacity), stability (stability), i.e. the ability of the concrete to remain homogeneous, resistance to segregation. Properties in the fresh state can be estimated by performing workability tests such as Slump Flow, L-Box, V-Funnel, U-Box, J-Ring. After curing, self-compacting concrete will possess the following properties: high mechanical strength, durability. The introduction of ultra-fine material is the real innovation because it tends to create a mixture composed mainly of tiny particles, capable of transporting coarse aggregates. Fly ash, when used correctly, has been observed to improve the properties of concrete in both fresh and hardened states.**

Index Terms— Self-compacting concrete; SCC; fresh properties; mechanical properties; fly ash.

I. INTRODUCTION

OVER the past forty years, self-compacting concrete (SCC) has shown clear advantages in working environment and technology. Due to its high fluidity, the SCC self-compacts automatically by its own weight and without the need for vibration during construction, which speeds up the work, reduces the use of human resources and increases the degree of freedom in the structural design. SCC also helps to prevent quality defects such as under-vibration, leakage, or over-vibration during the vibration process (Liu *et al.,*2023; Okamura & Ouchi, 2003).

Compared to ordinary concrete of the same strength, SCC is characterized by a lower water-to-binder ratio and a higher percentage of sand. Although its volumetric stability, mechanical properties, economy and durability are not satisfactory, its properties can be improved by incorporating mineral additives (Herath *et al.,*2021; Anjos *et al.,*2020), with the modifying effect of fly ash being the best (Jain *et al.,*2022). Singh *et al.,*(2019) showed that the addition of fly ash to the SCC could not only reduce the heat of hydration but also improve processability. Rabar et al (2021) reported that increasing fly ash content could improve the workability and flexural strength of SCC.

By correctly selecting the concrete ingredients, the performance of the concrete matrix in the face of the aggressive environment can be improved (Herath *et al.,*2021; Anjos *et al.,*2020). In addition, Hossain and Lachemi (2022) reported that performance criteria for the durability of reinforced concrete structures could be achieved to some extent using self-compacting concrete (SCC) instead of normally vibrated concrete (NVC) (Singh *et al.,* 2019).

C.D.C. is PhD candidate at Escuela Técnica Superior de Arquitectura de Madrid, Universidad Politécnica de Madrid.

The popularity/application of SCC has increased worldwide to improve the quality and functionality of concrete structures since its development in the late 80s in Japan (Faraj *et al.,* 2021; Ekenel, 2021). However, the application of the SCC on construction sites remains weak in many countries due to its high costs. The prerequisite for a greater mixture of cement and chemicals to achieve adequate workability characteristics makes SCC more expensive than NVC.

In addition, the higher cement content causes greater shrinkage and hydration heat problems, which in turn cause serious cracks and also damage the structural integrity by the attack of harmful substances in the concrete matrix (Okamura & Ouchi, 2003). In addition, the significant use of cement content in SCCs consistently leads to CO2 emissions. In recent decades, several attempts have been made (Ahmad & Alghamdi, 2014; Hossain & Lachemi, 2010; Okamura & Ouchi, 2003; Kasemchaisiri & Tangtermsirikul, 2008) to produce sustainable SCCs by replacing cement with secondary cementitious materials, such as fly ash. Replacing cement with these cementitious materials not only improves concrete performance but also reduces the cost of SCC and minimizes spillage and unwanted exploitation of natural resources.

In summary, the addition of an adequate amount of fly ash can refine and densify the microstructure of the SCC and further improve its mechanical properties and durability. Meanwhile, SCC is often used in complex structures and large projects. The heat of hydration of cementitious materials must be as low as possible to ensure volume stability during the setting and hardening process. Therefore, the preparation of SCCs with good mechanical properties by replacing cement with a large volume of fly ash has considerable application potential.

This study analyzes and summarizes some of the main results regarding the properties of self-compacting concrete with fly ash.

In particular, the results obtained in an experimental study conducted by Madasu Durga Rao *et al.,*(2023) on the characterization of fiber-reinforced self-compacting concrete using fly ash and cement, an experimental study on fly ash in the properties of self-compacting concrete, conducted by S. Anandaraj *et al.,*(2022), experimental research of SCC with fly ash conducted by N. Karthiga *et al.,* (2023), Resistant behavior of green concrete with fly ash by analyzing the results obtained by C. Anish *et al.,* (2023), fresh and mechanical properties of SCC with fly ash analyzed by Arunchaitanya Sambangi *et al.,* (2021).

The article focuses on the behavior of self-compacting concrete (SCC) based on fly ash. The overall behavior of SCCs was estimated from the observations of the available literature in terms of fresh, mechanical and durability properties. The results of the various investigations show that the substitution of binder and aggregates affects properties in the fresh state (Sambangi & Arunakanthi, 2021); mechanical (Rao *et al.,* 2023; Anandaraj *et al.,* 2022; *Karthiga-Shenbagam et al.,* 2023; Anish *et al.,* 2023) and durability of the SCC. The literature indicates that SCCs made with specific levels of fly ash (FA) do not inhibit overall performance, in fact improve it (Anandaraj *et al.,* 2022; Sambangi & Arunakanthi, 2021).

In addition, the study also supports minimizing the overload of natural resources to achieve the desired sustainability (Anish *et al.,* 2023).

The economical, flexible, sustainable and strong characteristics of concrete have demonstrated its ability to be the most successful building component in the world. The tendency to design complex structures leads to the occurrence of vibration/compaction problems due to reinforcement congestion. The aforementioned characteristics and some of the few limitations have favored the growth of self-compacting concrete (SCC). Over the past few decades, the SCC has gained great global recognition. It reduces concerns about noise and compaction, unlike regular vibrated concrete (HNV). In addition, the introduction of SCC has reduced the total concrete construction period in most civil engineering projects. Due to its improved properties in the fresh state, it possesses enough viscosity to handle segregation, as it flows at a uniform level only by gravity.

According to previous studies, the annual global production of fly ash (FA) is estimated at more than 800 million tonnes. In addition, it has been predicted that most of the amount of fly ash generated will be dumped in landfills, posing additional problems such as soil scarcity and environmental pollution.

These uses can solve three problems simultaneously, such as 1) Reducing construction costs 2) Solving local landfill problems 3) Reducing the total amount of cement concrete in concrete preparation (Rao *et al.,* 2023).

The objective of this study is the analysis of the properties of self-compacting concrete with fly ash, examining the mechanical properties, durability and workability. The main objective is to delve into the effects of fly ash on the performance of self-compacting concrete, contributing to its understanding and optimization in the context of sustainable construction and waste management.

II. MATERIALS AND METHODS

A. *Self-compacting concrete*

Self-compacting concrete is a type of concrete characterized by considerable deformability in its fresh state, which allows the mixture to be easily placed in the formwork without compromising its qualities of homogeneity and resistance. The advantages of an extremely fluid product are intuitive and converge towards the acceleration of construction activities. There is therefore an added value for concrete technology, compared to the usual guarantees of rheological properties, which is manifested in the speed of pouring and the resulting savings.

High fluidity, which allows fresh concrete to undergo great deformations, is the prerequisite for self-compaction, the main rheological characteristic of this type of concrete.

The high fluidity, which allows fresh concrete to suffer considerable deformations, is a prerequisite for self-compaction, the main rheological characteristic of this type of concrete. This fluidity, of course, does not limit the other qualities, but keeps them unaltered, thus guaranteeing uniformity as a constant composition at all points, an essential element for the quality and characteristics of the final product. The characteristics in the fresh state all converge towards self-compaction, since each of them is a necessary condition for the concrete to be able to be arranged autonomously in the formwork by the only gravitational force, without the need for vibration (Liu *et al.,* 2023; Okamura & Ouchi, 2003; Anjos *et al.,* 2020; Ausiello, 2018).

B. *Rheological properties*

To be self-compacting, concrete must possess certain rheological properties. The remarkable fluidity is associated with the so-called "filling ability", which is manifested in the ability to completely fill the formwork, even if they are complex and articulated, using only their own weight. Hence the ease of placement between reinforcements, called "passing ability", which allows it to be used effectively in highly reinforced, structurally complex, thin or narrow sections. Added to these properties in the fresh state is "stability", the ability of concrete to remain uniform during transport and placement. In fact, the ability to flow, as a requirement of self-compacting concrete, must constitute an added value with regard to the homogeneity of the compound, which is naturally essential to guarantee mechanical resistance. The presence of homogeneity inevitably implies a resistance to segregation, which means that the density and therefore the elasto-mechanical properties remain the same throughout the mixture (Liu *et al.,* 2023; Okamura & Ouchi, 2003; Ausiello, 2018).

C. *Mechanical properties*

The rheological properties translate, in a hardened state, into remarkable performance, ranging from high mechanical resistance to exceptional quality which, in general terms, is an indispensable characteristic for industrialized products of the contemporary era. In particular, quality also means durability, understood as the ability of concrete to maintain its design performance throughout its expected rated service life, making it a crucial design parameter. Therefore, the advantages observed in self-compacting concretes in their fresh state do not limit the characteristics of the final product at all, but, on the contrary, highlight their remarkable fluidity capacity, achieved without an excessive increase in the amount of water, thus maintaining a low water/cement ratio. This condition is the first guarantee of high mechanical strength, which in turn is essential for durability (Okamura & Ouchi, 2003; Ausiello, 2018).

D. *Mixture*

As far as aggregates are concerned, the aggregate content varies considerably, with a significant decrease in the volume of coarse aggregates and, consequently, a more or less significant increase in fine aggregates.

The amount of water does not increase significantly, as it remains proportional to the amount of cement to be hydrated and the aggregates to be moistened, to the detriment of the rate of workable water, which is contained to the maximum.

The amount of water, proportional to cement and aggregates, is contained through the use of superplasticizers, reducing the water-cement ratio compared to ordinary concrete, improving strength and durability.

The amount of cement remains relatively stable thanks to the addition of filler, which acts physically in the fresh phase.

The key innovation in self-compacting concretes is the introduction of ultra-thin material, creating a cement system with tiny particles that transports the coarse aggregates. The composition aims to increase the conveying fluid (the paste) and reduce the conveyed phase (the coarse aggregates), resulting in a smoother mix. The infill also contributes to cohesion without excessively increasing the amount of cement. The transported phase, composed mainly of coarse aggregates, is kept in a reduced quantity to facilitate transport and minimize collisions between the aggregates and the reinforcement (Okamura & Ouchi, 2003; Ausiello, 2018).

E. *Filler*

The role of the extremely thin material, known as filler, in the design of self-compacting concretes is to promote an increase in carrier fluid, allowing easy movement in the structure. However, if the same result were obtained by increasing the amount of cement, there would be a greater risk of thermal gradients, which would cause cracking due to the high shrinkage. Therefore, the goal of increasing the carrier fluid is achieved by supplementing the cement with filler, which can be, for example, ground limestone, fly ash, silica fume, blast furnace slag or ground pozzolana. These materials are distinguished by their slow or no rate of hydration during the reaction.

The term "filler" comes from English and literally translated means "filler", thus identifying its role as an extremely small aggregate. In the composition of concretes, filler acts by improving the granulometric assortment of aggregates, increasing the fine fraction to limit the risks of segregation.

The physical action of fillers in fresh mix consists mainly of simulating a virtual increase in the amount of cement. By not actively participating in the hydration reaction, they do not cause the problems associated with excessive heat development in the hardened state. As a result, the rheological properties of the mixtures are improved, with a greater attention to workability, which is mainly entrusted to the carrier fluid (Ausiello, 2018)

F. *Fly ash*

The combustion of coal in thermal power plants produces fly ash in large quantities, which are considered primary waste and are usually disposed of in large areas, causing damage to the environment and the health of the surrounding communities.

During coal combustion, mineral impurities melt to form ash that, when cooled over time, solidifies into spherical particles of a glassy nature known as FA. In construction, FA is mainly used as a substitute for Portland cement in concrete, as its spherical shape improves flow properties and mixes freely within concrete. The use of AM contributes to reducing CO2 emissions generated by the cement industry and improves the workability characteristics of concrete.

Fly ash is mainly composed of silicate glass and contains silica, alumina, iron, calcium, magnesium, sulfur, sodium,

TABLE I
DOSAGES USED IN 13

Mix	Cement (kg/m^3)	Fly ash (kg/m^3)	Fly ash (%)	S (%)	Steel fibre (%)	F.A (kg/m^3)	C.A (kg/m^3)	Water (kg/m^3)	SPn (kg/m^3)
F0	550	0	0	–	-	924.52	779.35	165	2.2
F5	522.5	27.5	5	–	-	920.4	775.87	165	2.09
F10	495	55	10	–	-	916.28	772.4	165	1.98
F15	467.5	82.5	15	–	-	912.15	768.92	165	1.87
F20	440	110	20	–	-	908.03	765.44	165	1.76
F25	412.5	137.51	25	–	-	903.91	761.97	165	1.65
F30	385	165	30	–	-	899.78	758.50	165	1.54

potassium, and carbon as minor constituents.

Its use is widespread in civil engineering, especially in the concrete industry. In addition to concrete production, FA is used as a substitute for PC, helping to reduce the dose of superplasticizer needed and improving rheological behavior by minimizing the risk of cracking.

In general, the use of AM in Portland cement production is widespread, recognized as an environmentally friendly material due to its low embodied energy, low water absorption rate, and self-cementing hydraulic character, which make it effective under normal and severe conditions (Liu *et al.,* 2023; Anjos *et al.,* 2020; Ausiello, 2018).

G. *Dosages*

To evaluate the influence of fly ash on self-compacting concrete (SCC), several studies adopted varying mix designs with different levels of cement replacement and admixture compositions. In the study by S. Anandaraj *et al.,* (2022), two primary mix designs were employed: a conventional control concrete (CC) mix with 100% ordinary Portland cement and a modified mix incorporating 25% fly ash (FA), resulting in a 75% cement and 25% FA blend. This binary blend aimed to assess the fresh and hardened properties of SCC when a moderate portion of cement was substituted by fly ash.

N. Karthiga *et al.,* (2023) introduced a more complex experimental design, combining fly ash with groundnut shell ash (AGO) and granite dust (GD). The control mix (GD0FA0) contained 546 kg/m^3 of cement and no FA or GD, while the modified blends (GD20FA20 and GD0FA30) replaced cement with varying proportions of FA and GD. For instance, in the GD20FA20 mix, 20% of both FA and GD were incorporated by partially substituting cement and fine aggregates, respectively. These mixes were carefully proportioned to maintain a consistent water content (201.8 l/m^3), and the superplasticizer dosage was adjusted between 0.8% and 1.35% to ensure adequate flowability, a key characteristic of SCC. This study allowed for the observation of synergistic effects between FA and other industrial by-products on both fresh and hardened properties.

In a more pronounced substitution strategy, C. Anish *et al.,* (2023) evaluated a high-volume fly ash mixture, replacing 50% of the cement content with FA. The study compared this mix (FAC-1) against a control concrete mix composed entirely of cement (CC), aiming to investigate the feasibility of substantial cement reduction without compromising mechanical strength and workability. Similarly, Sambangi *et al.,*(2023= conducted a detailed parametric analysis by preparing a series of seven SCC mixes with incremental fly ash replacements ranging from 0% to 30% in 5% intervals. Each mix, labeled from C + F0 to C + F30, maintained a constant total binder content (cement plus fly ash) of 550 kg/m^3, a uniform water-to-powder ratio of 0.3, and consistent water and superplasticizer dosages across all variants. Coarse and fine aggregates were proportionally adjusted to ensure proper packing density and segregation resistance.

Together, these mix designs provide a broad spectrum of cement replacement strategies—from moderate to high-volume fly ash incorporation—and highlight the versatility of SCC when modified with supplementary cementitious materials. By standardizing parameters such as the water/powder ratio and superplasticizer content, while varying the proportions of cement, FA, and other mineral additions, these studies collectively offer valuable insights into the performance optimization of sustainable SCC formulations.

H. *Tests performed*

Several experimental studies were consulted to evaluate the performance of self-compacting concrete (SCC) incorporating fly ash. These studies included both fresh and mechanical property tests to comprehensively assess the behavior of SCC under various conditions. In the fresh state, five main tests were employed to determine the workability and flow characteristics: the slump flow test, T50 time, V-funnel test, L-box test, and U-box test. Studies conducted by Rao *et al.,* (2023), Karthiga-Shenbagam *et al.,* (2023), and Sambangi & Arunakanthi, (2021) conducted all five tests, ensuring a broad evaluation of the material's rheological behavior. Anandaraj *et al.,* (2022) performed all the tests except the slump flow test, while Anish *et al.,* (2023) did not report any fresh property evaluation.

In terms of mechanical performance, the selected studies assessed compressive strength, split tensile strength, and flexural strength. Rao *et al.,* (2023) was the most comprehensive, incorporating all three mechanical tests alongside all fresh state tests. Anandaraj *et al.,* (2022) and Sambangi & Arunakanthi, (2021) also conducted a full set of mechanical evaluations, while Karthiga-Shenbagam *et al.,* (2023) focused only on compressive strength. Anish *et al.,* (2023), although lacking in fresh property data, contributed mechanical insights through split tensile and flexural strength tests. This combination of studies provides a well-rounded basis for understanding how fly ash influences both the fresh and hardened properties of SCC.

The European Federation of National Associations Representing producers and applicators of specialist building

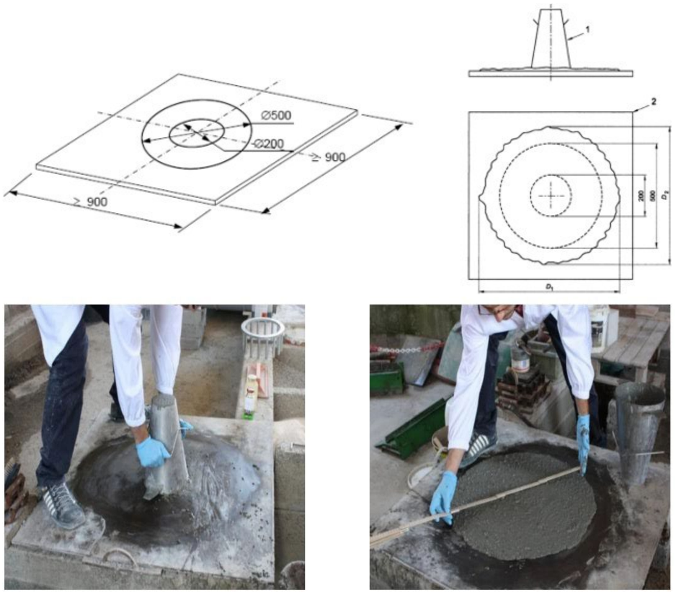

Fig. 1. Slump Flow test

products for Concrete (EFNARC) provides comprehensive guidelines outlining the performance requirements for self-compacting concrete (SCC), particularly in the fresh state [20]. According to these guidelines, SCC must meet specific limits in various standard tests to ensure its filling and passing abilities. The slump flow diameter, which evaluates filling ability, should fall within the range of 650–800 mm. The T50 time, indicating the viscosity of the mix, should range between 2 and 5 seconds. For the V-funnel test, which also measures filling ability, acceptable flow times range from 6 to 12 seconds. Passing ability is assessed through the L-box and U-box tests, with EFNARC recommending an L-box ratio (H2/H1) between 0.8 and 1.0, and a U-box height difference (H2–H1) between 0 and 30 mm.

To evaluate mechanical performance in the hardened state, three standard tests were considered across the reviewed literature: compressive strength, split tensile strength, and flexural strength. Rao *et al.,* (2023), Anandaraj *et al.,* (2022) and Anish *et al.,* (2023) conducted a tope set of mechanical tests, providing a comprehensive assessment of the structural performance of SCC with fly ash. Karthiga-Shenbagam, (2023) reported only compressive strength, while article Sambangi & Arunakanthi, (2021) included both compressive and split tensile strength evaluations. These tests are critical to understanding the long-term performance and durability of SCC mixtures, especially when incorporating supplementary cementitious materials like fly ash.

I. *Slump flow test e T50*

The Abrams cone used to measure settlement in traditional concretes can be used to assess the flow capacity of self-compacting concrete in the absence of obstructions, as well as to extract useful indications about the tendency of the mixture to flow segregation. The test involves placing the concrete inside the Abrams cone resting on a smooth 900 x 900 mm slab and then lifting it, letting the concrete flow, and activating a timer as it is lifted (Okamura & Ouchi, 2003; Faraj *et al.,* 2021; EFNARC, 2005).

Fig. 2 V funnel test.

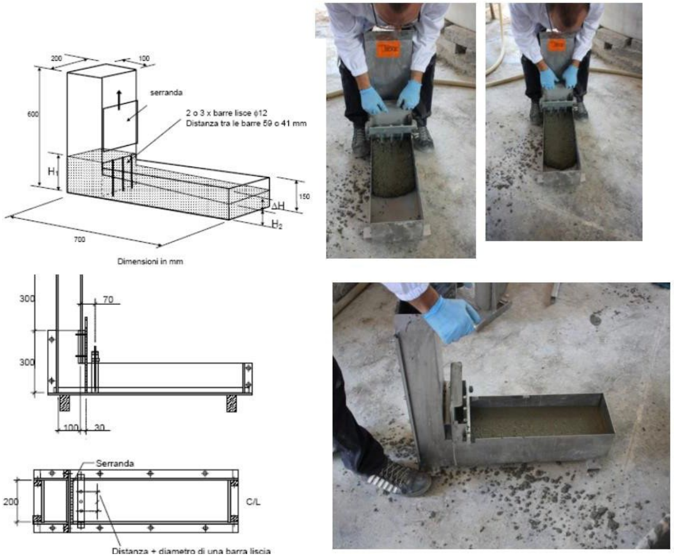

Fig. 3. L-Box

The determinations that are carried out are the following

- time required for the concrete to settle to a diameter of 500 mm (T50);
- Final settling diameter of the concrete (Df = settling-flow) after it has stopped flowing, which is the mean of two diameters D1 and D2 measured orthogonally.

The slump-flow measurement is proportional to the flow capacity of the material in the absence of obstacles: the higher the df value, the greater the deformability of the material, i.e. its ability to reach areas distant from the point of introduction of the concrete into the formwork.

T50 values, on the other hand, are related to the viscosity of the material and thus indirectly to segregation resistance (Okamura & Ouchi, 2003; Faraj *et al.,* 2021; EFNARC, 2005).

J. *V-funnel*

The segregation resistance of self-compacting concrete can also be determined by the V-funnel test: it consists of measuring the time it takes for concrete to completely exit a V-shaped funnel immediately after finishing mixing the mixture (Okamura & Ouchi, 2003; Faraj *et al.,* 2021; EFNARC, 2005).

K. *L-box*

The L-shaped box consists of a vertical portion into which the concrete is introduced, which is initially prevented from flowing from below thanks to the presence of a lock gate; When opened, the mixture flows into the horizontal portion of the equipment through a grid made up of two or three vertically arranged reinforcements. The passing capacity is evaluated by measuring the difference in height of the mixture at the furthest point (h1) reached and the difference evaluated behind the lock

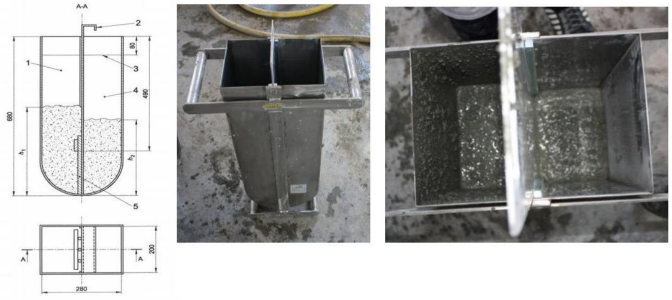

Fig. 4. U-Box

in the vertical part of the equipment (h2). The passage capacity will be greater the closer the h1/h2 ratio is to 1 and is considered sufficient (according to EFNARC recommendations) if the h1/h2 ratio is at least 0.80 (Okamura & Ouchi, 2003; Faraj *et al.,* 2021; EFNARC, 2005).

L. *U-box*

The U-shaped box (developed at the Taisei Corporation Research and Technology Center in Japan) consists of a rectangular section duct divided into two compartments by a central lifting hatch. Between the two compartments is placed a grid made up of reinforcement bars of 13 mm in diameter at 50 mm between centers, which creates a space of 35 mm between the bars. The section on the left is filled with concrete; Once the gate is opened, the concrete flows upwards into the other compartment, through the grating, and the height of the concrete in both sections is measured. If concrete flows freely like water, at the end of the flow motion, it will be at the same level in both compartments, so Δh called fill height = H2-H1=0. Therefore, the closer the test value is filled height to zero, the more fluid the concrete will be (Okamura & Ouchi, 2003; Faraj *et al.,* 2021; EFNARC, 2005).

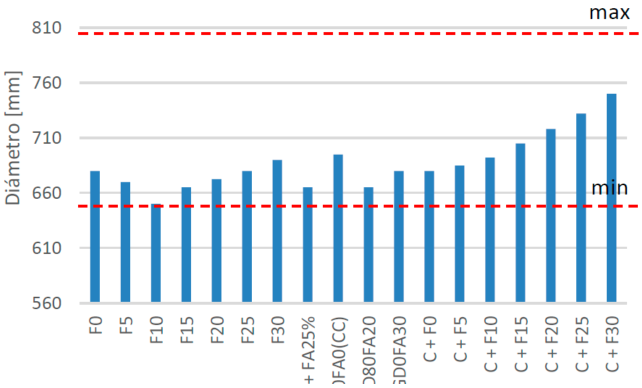

Fig. 5. Slump flow test results.

III. RESULTS

A. *Fresh-state test results*

Table 2 shows the results of the tests carried out on concrete with fresh fly ash.

The performance of self-compacting concrete (SCC) in the fresh state was evaluated through a series of standard tests in accordance with EFNARC guidelines, which establish acceptable ranges for flowability and passing ability. The slump flow test results, illustrated in Fig. 5, indicate that all SCC mixtures exhibited flow diameters within the recommended range of 650–800 mm, confirming adequate filling ability and self-compactability. These results suggest that the mixtures possess sufficient viscosity and cohesiveness to flow under their own weight without segregation.

Fig. 6 presents the outcomes of the T50 test, which measures the time required for the mix to spread to a 500 mm diameter. Most of the SCC mixtures met the EFNARC criterion of 2–5 seconds; however, one mix—specifically GD80FA20—

TABLE II
FRESH-STATE TESTS RESULTS

	Mix	Slump (mm)		T500 time (s)		V-funnel		L-box		U-box	
art 1 [13]	F0	680		3,9		7,5		0,9		10	
	F5	670		4		7,2		0,9		12	
	F10	650		3,6		8,1		0,9		15	
	F15	665		4,5		6,8		0,9		17	
	F20	673		3		4,3		0,9		20	
	F25	680		4,4		4,8		0,9		19	
	F30	690		3,2		5,5		0,9		17	
art 2 [14]	c+ FA25%	665	ref= 650-800 mm EFNARC guidelines	-	rif=2-5 sec EFNARC guidelines	10	rif= 6-12 sec EFNARC guidelines	0,9	rif= H2/H1=0.8- 1 EFNARC guidelines	22	rif= H2/H1= 30 mm (max) EFNARC guidelines
art 3 [15]	GD0FA0(CC)	695		4		7,8		0,9		-	
	GD80FA20	665		7,4		17		0,8		-	
	GD0FA30	680		2,7		5		1		-	
art 5 [17]	C + F0	680		4,3		9,4		0,8		28	
	C + F5	685		4,3		9,3		0,8		28	
	C + F10	692		4,1		9		0,8		27	
	C + F15	705		4		8,6		0,8		26	
	C + F20	718		3,7		8,2		0,8		25	
	C + F25	732		3,4		8,1		0,8		23	
	C + F30	750		3,2		7,6		0,9		21	

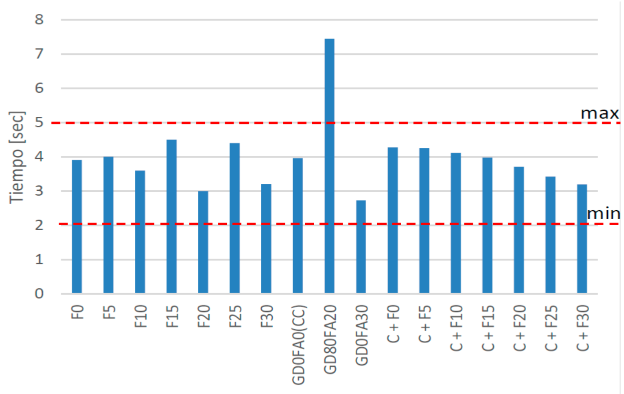

Fig. 6. T50 Results.

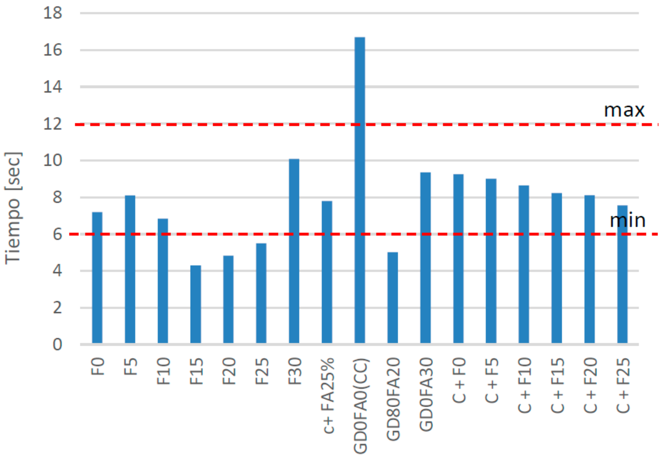

Fig. 7. V-funnel results

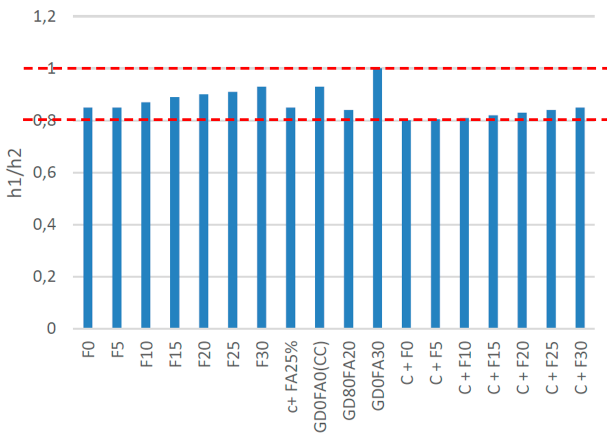

Fig. 8. L-box results

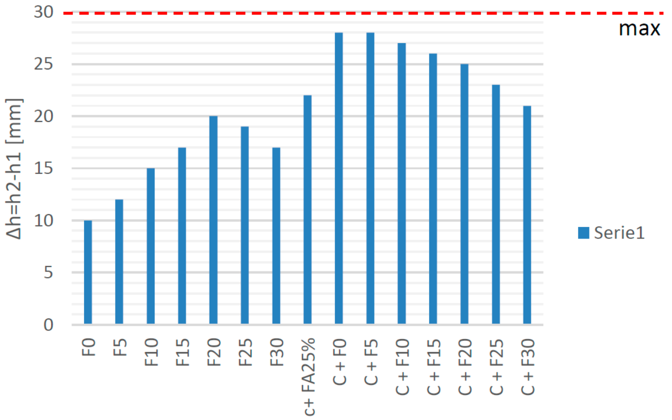

Fig. 9. U-Box results

exceeded the upper limit. This deviation suggests a higher viscosity or resistance to flow in that particular blend, potentially due to the combined influence of elevated granite dust content and reduced superplasticizer dosage.

In the V-funnel test, shown in Fig. 7, which evaluates flow time through a confined section, the results were more variable. EFNARC recommends values between 6 and 12 seconds. However, nine mixtures fell outside this range—eight exhibited flow times below the lower limit, indicating overly fluid or unstable mixes, while one exceeded the upper limit, pointing to increased viscosity and reduced flowability. These variations highlight the sensitivity of SCC behavior to adjustments in mix composition, especially with the incorporation of supplementary materials like fly ash and fine fillers.

Passing ability was assessed using both the L-box and U-box tests. As shown in Fig. 8, the L-box results for all mixtures fell within the acceptable range of 0.8 to 1.0 (H2/H1 ratio), indicating good passing ability without significant blocking or segregation around reinforcements. Similarly, Figure 9 displays the results of the U-box test, where all measurements were within the 0–30 mm limit for the height difference (H2–H1), further confirming that the SCC mixtures retained adequate flow under restricted conditions. These findings collectively demonstrate that, with a few exceptions, the SCC mixes met the EFNARC criteria for fresh state performance, validating their suitability for use in construction applications requiring high flowability and self-compaction.

In the V-funnel, values are not between 4 and 12 s, i.e. 8 mixtures below the lower limit and 1 case exceeds the upper limit (EFNARC guidelines).

B. *Hardened state test results*

The hardened state behavior of self-compacting concrete (SCC) with partial replacement of cement by fly ash was evaluated through compressive strength, tensile strength, and flexural strength tests at different curing ages. The mechanical response varied depending on the replacement percentage, curing time, and the presence of additional materials.

In the study by Rao *et al.,* (2023), compressive strength increased progressively with fly ash replacement up to 20%, reaching a peak value of 73 MPa at 90 days. The reference mix (F0) achieved 62 MPa, while the F20 mix outperformed all others, indicating enhanced pozzolanic activity at this replacement level. Fly ash contents above 25% (F25 and F30) led to a reduction in strength, though the values remained comparable to the reference. This trend highlights the optimal performance window of 15–25% replacement, where sufficient cement remains to ensure early strength, while fly ash contributes to long-term strength gains. The early-age strength (3 to 7 days) was generally lower across all fly ash mixes, consistent with the slower reactivity of fly ash.

Anandaraj *et al.,* (2022) observed a compressive strength of 26 MPa at 14 days in their mix with 25% fly ash (C + FA25%), which is considerably lower than results in other studies. This suggests that differences in binder content, water-to-binder ratio, or curing practices may significantly influence the early and mid-term performance of fly ash concretes. In Karthiga *et al.,* (2023), where fly ash was combined with granite dust, the control mix (GD0FA0) reached 38 MPa at 28 days. However, performance decreased notably in the GD0FA30 mix (20 MPa), indicating that high-volume replacement and the presence of multiple mineral additives can compromise strength.

In the work by Anish *et al.,* (2023), a 50% fly ash replacement (FAC-1) resulted in a compressive strength of 38.6 MPa at 28 days, slightly below the control mix (CC) which reached 39.8 MPa. Despite the high replacement level, the reduction was marginal, pointing to the potential for high-volume fly ash use when supported by suitable mix design. Similarly, Sambangi *et al.,*[17] studied SCC with fly ash contents ranging from 5% to 30%. The highest compressive strength, 74 MPa at 28 days, was obtained with 20% replacement (C + F20), reaffirming the effectiveness of moderate fly ash levels. Above this threshold, a gradual strength reduction was observed, with the 30% replacement mix (C + F30) reaching 68 MPa.

Tensile strength results showed comparable trends. In Rao *et al.,* (2023), the reference mix achieved 3.35 MPa at 90 days, while mixes with 15–25% fly ash recorded higher values. The F20 mix reached 4.85 MPa, showing the most significant improvement. Moderate increases were also noted for F15 and F25, while F30 showed a decline to 3.3 MPa. In Anandaraj *et al.,* (2022), the mix with 25% fly ash reached only 1.7 MPa at 28 days—substantially lower than the values in the study conducted by Rao *et al.,* (2023), likely due to differences in overall binder content or water ratio. In [16], the control mix had a tensile strength of 8.4 MPa at 28 days, while the FAC-1 mix reached 5.25 MPa, showing a noticeable reduction with 50% fly ash. Sambangi *et al.,*[17] reported a similar optimal range: the C + F20 mix reached 4 MPa at 28 days, while higher replacements (C + F25 and C + F30) yielded lower tensile strengths of 3.7 MPa and 3.4 MPa, respectively.

Regarding flexural strength, Rao *et al.,* (2023) again reported peak performance in the 15–25% fly ash range. The F0 control mix reached 9 MPa at 90 days, while F15 and F20 both matched this result. F25 achieved 8.3 MPa, with a slight drop observed in F30 (8.1 MPa). These results confirm that fly ash can maintain or even slightly enhance flexural behavior when used within a moderate range. In [14], the flexural strength at 28 days was limited to 4 MPa for the 25% FA mix, again significantly lower than values from Rao *et al.,* (2023). Karthiga *et al.,*(2023) reported 5 MPa for all mixes at 28 days, including those with granite dust, suggesting that secondary materials did not enhance flexural resistance. In Anish *et al.,* (2023), the FAC-1 mix reached 5.4 MPa compared to 7.2 MPa in the control, indicating a notable reduction with 50% replacement. Lastly, Sambangi & Arunakanthi, (2021) values for the C + F20 mix remained favorable around 9 MPa, while the higher fly ash contents again led to modest declines.

Overall, these results confirm that fly ash can effectively replace cement in SCC, particularly in the 15–25% range. This substitution not only maintains but can even enhance compressive, tensile, and flexural strength over time. However, exceeding 25–30% fly ash typically results in diminished early strength and a modest drop in long-term mechanical performance. The variations observed across studies underscore the importance of tailored mix design, adequate curing, and controlling supplementary material interactions to maximize the benefits of fly ash in SCC.

IV. CONCLUSIONS

In this article, the rheological and mechanical properties of self-compacting concrete with various percentages of fly ash are studied. Studies conducted on self-compacting concrete with the addition of fly ash unequivocally attest to the benefits of this material for self-compacting concrete. Fly ash, with its special properties, has proven to contribute significantly to the improvement of the fresh and hardened characteristics of concrete, thus confirming its role as an effective adjuvant in the production of advanced and sustainable building materials. Overall, the results suggest that the addition of fly ash can improve both the fresh and hardened properties of concrete, specifically:

- The result of the test shows that fly ash is able to improve properties in both fresh and hardened states.
- The fly ash content influenced the fresh properties of the SCC.
- In the case of the settlement flow, all SCC mixtures show suitable settlement movements in the range of 650-800 mm (EFNARC guidelines).
- In the T50 test, one case exceeds the limit (EFNARC guidelines)
- Similarly, in the V-tunnel, 9 time values are not between 4 and 12 s, i.e. 8 mixtures below the lower limit, and 1 case exceeds the upper limit (EFNARC guidelines)
- • The values of the L-box tests are between 0.8 and 1 (EFNARC guidelines).
- • U-box tests are also within the limit imposed by the EFNARC guidelines
- The strength increases with the decrease in the water/cement ratio (a/c) and reaches a better toughness at an a/c of 0.3.
- It can be observed that the effects on mechanical properties may vary depending on the type of design of the starting mixture, since in this study different items were compared, therefore different starting mixtures.
- It can be observed that as the amount of fly ash increases, the compressive strength, split tensile strength, and flexural strength increase, but this occurs to a certain extent, from which the increase in the percentage of fly ash no longer leads to an increase in mechanical properties, but, on the contrary, it diminishes them. In general, maximum strength is achieved with a fly ash content of 20%.
- The addition of fly ash or silica fume, as well as the use of superplasticizers, has generally led to higher tensile strength by splitting than conventional concrete.
- In general, the addition of fly ash and the use of superplasticizers resulted in a decrease in compressive strength in the initial phases but resulted in higher strength in the later phases.
- The addition of fly ash can significantly improve compressive strength, tensile strength, and flexural strength.
- Its ability to optimize the workability and mechanical

strength of concrete, combined with its ecological character derived from combustion residues, opens up promising prospects for the construction industry, as it reduces the amount of cement needed. Therefore, the use of this material in concrete can be recommended as an environmentally friendly and sustainable practice in the construction industry, encouraging the adoption of innovative and environmentally friendly solutions..

ACKNOWLEDGEMENTS

I would like to express my sincere thanks for the support and opportunity provided during the conduct of this research work. In particular, I would like to thank the Polytechnic University of Madrid (UPM) for hosting this congress and providing a platform for scientific exchange. My sincere thanks also to the University of Naples Federico II, my home university, for the continued support and stimulating learning environment. This Erasmus exchange experience has greatly enriched my academic career and has contributed to the realization of this work.

REFERENCES

Ahmad, S., & Alghamdi, S. A. (2014). A statistical approach to optimizing concrete mixture design. *The Scientific World Journal, 2014*, Article 561539. https://doi.org/10.1155/2014/561539

Anandaraj, S., Karthik, S., Elango, K. S., Nishiketan, S., Pandiyarajan, G., Nithis Kumar, P., Palanikumar, R., & Harihanandh, M. (2022). An experimental study on Fly Ash (FA) and marble powder in the properties of Self-Compacting Concrete (SCC). *Materials Today: Proceedings, 52*(3), 1771–1774. https://doi.org/10.1016/j.matpr.2021.11.441

Anish, C., Venkata Krishnaiah, R., & Vijaya Bhaskar Raju, K. (2023). Strength behavior of green concrete by using fly ash and silica fume. *Materials Today: Proceedings.* https://doi.org/10.1016/j.matpr.2023.04.604

Ausiello, G. (2018). *Fluid concrete for fluid architectures* (2nd ed.). Luciano.

Faraj, R. H., Sherwani, A. F. H., Jafer, L. H., & Ibrahim, D. F. (2021). Rheological behavior and fresh properties of self-compacting high strength concrete containing recycled PP particles with fly ash and silica fume blended. *Journal of Building Engineering, 34*, 101667. https://doi.org/10.1016/j.jobe.2020.101667

Herath, C., Gunasekara, C., Law, D. W., & Setunge, S. (2021). Long term mechanical performance of nano-engineered high volume fly ash concrete. *Journal of Building Engineering, 41*, 103168. https://doi.org/10.1016/j.jobe.2021.103168

Hossain, K. M. A., & Lachemi, M. (2010). Fresh, mechanical, and durability characteristics of self-consolidating concrete incorporating volcanic ash. *Journal of Materials in Civil Engineering, 22*(7), 651–657. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000063

Jain, A., Choudhary, S., Gupta, R., Chaudhary, S., & Gautam, L. (2022). Effect of granite industry waste addition on durability properties of fly ash blended self-compacting concrete. *Construction and Building Materials, 340*, 127727. https://doi.org/10.1016/j.conbuildmat.2022.127727

Kasemchaisiri, R., & Tangtermsirikul, S. (2008). Properties of self-compacting concrete incorporating bottom ash as a partial replacement of fine aggregate. *ScienceAsia, 34*(1), 87–95.
https://doi.org/10.2306/scienceasia1513-1874.2008.34.087

Karthiga-Shenbagam, N., Saravanan, M., Aishwarya, M., & Vinssilin Joanlia, D. (2023). Production, experimental investigation of SCC using fly ash and granite debris. *Materials Today: Proceedings.* https://doi.org/10.1016/j.matpr.2023.04.592

Liu, J., Zang, S., Yang, F., Hai, R., & Yan, Y. (2023). Fracture properties of steel fibre reinforced high-volume fly ash self-compacting concrete. *Case Studies in Construction Materials, 18*, e02110. https://doi.org/10.1016/j.cscm.2023.e02110

Madasu Durga Rao, Dey, S., & Panduranga Rao, B. (2023). Characterization of fiber reinforced self-compacting concrete by fly ash and cement. *Chemistry of Inorganic Materials, 1*, 100010. https://doi.org/10.1016/j.cinorg.2023.100010

Mahmut, E. (2021). Fiber reinforced polymer reinforcement for concrete members—ACI Committee 400 is taking the next step toward building code compliance. *Concrete International.*

Okamura, H., & Ouchi, M. (2003). Self-compacting concrete. *Journal of Advanced Concrete Technology, 1*(1), 5–15. https://doi.org/10.3151/jact.1.5

Sambangi, A., & Arunakanthi, E. (2021). Fresh and mechanical properties of SCC with fly ash and copper slag as mineral admixtures. *Materials Today: Proceedings, 45*(7), 6687–6693. https://doi.org/10.1016/j.matpr.2020.12.144

Singh, N., Kumar, P., & Goyal, P. (2019). Reviewing the behaviour of high volume fly ash based self compacting concrete. *Journal of Building Engineering, 26*, 100882. https://doi.org/10.1016/j.jobe.2019.100882

Reconocimiento – NoComercial (by-nc): Se permite la generación de obras derivadas siempre que no se haga un uso comercial. Tampoco se puede utilizar la obra original con finalidades comerciales.