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The use of recycled aggregates for High-performance Self-compacting concrete production

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ABSTRACT

Due to the favorable characteristics of Self-compacting Concrete (SCC) and the unique properties of High-Performance Concrete (HPC), as well as its rising application in the construction industry, this type of concrete remains the matter of interest and research. Also, due to the environmental issues connected with natural aggregates in concrete production, replacing natural aggregates with recycled aggregates is a more sustainable technique to produce concrete. This project investigates the use of recycled fine aggregates (RFA) for high-performance self-compacting concrete.

The impact of three types of recycled fine aggregates (Ceramic, Concrete and Mixed) on the physical, mechanical and durability properties of concrete was evaluated. For that, many tests have been conducted to analyse the behavior of this type of concrete. Also, the influence of the incorporation of fly ash in this particular concrete with 30% and 50% replacement was assessed. Moreover, the analysis of autogenous shrinkage to determine the possibility of RFAs as an internal curing agent. Also, this type of concrete's capacity to continue performing its intended purpose while maintaining its serviceability and durability by the drying shrinkage and chloride diffusion.

The test results in general showed that this type of concrete fulfilled the SCC requirements and that concrete with recycled ceramic aggregates showed higher compressive strength than conventional concrete and can act as an internal curing agent. However, the concretes with RFAs have low chloride resistance when mixed with only 100% Portland cement.

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1. Chapter 1: Introduction

1.1. General aspects

Concrete is the most used material in building and construction, it is widely used because of its high compressive strength, high durability, low cost and it can be cast to any shape. Concrete contains natural resources as aggregates, consists of manufactured crushed stone and sand created by crushing bedrock, or naturally occurring unconsolidated sand and gravel. The fraction of aggregates represent 75% of its total volume and subsequently it plays an indispensable role in the general performance of concrete (Huang & Zhao, 2009). Accordingly, there has been an attention on developing sustainable resources within the construction industry, thus, by using recycled aggregates. Nonetheless, since it is widely thought that the innovation in binder materials can help to develop innovative concrete material, more consideration has been paid to the development of novel binding phases of concrete. As the worldwide demand increases for infrastructure, it places a major concern on the environment. Indeed, recently a considerable advancement has been observed in this field such as the development of High-performance concrete and Self-compacting concrete.

The production of a highly workable concrete known as Self-Compaction Concrete (SCC) has steadily gained popularity. In comparison to conventional concrete, SCC has higher binder contents in addition to various chemical admixtures and supplementary cementitious materials (Aslani et al., 2018). SCC is well-known for its capability to flow easily through congested reinforcement and self-compact under its own weight with minimal to no mechanical vibration required (Aslani et al., 2018). Also, another innovative type of concrete is High-Performance Concrete (HPC), it has three characteristics: high strength, high durability and high workability according to (Islam Laskar, 2011).

Another major development is the use of recycled aggregates in concrete (RA). RA are a construction material originated from construction and demolition waste that is cleaned and crushed into a material with a specified size and quality. It is divided based on the particles size into fine recycled aggregates and coarse recycled aggregates. In general, RA contains bricks, cement mortar, concrete, natural aggregate (stone) and the separation of different kinds of these wastes is very much essential before using them in various applications. Though there are some benefits of recycled aggregate concrete in terms of economic, environmental and saving natural resources, there are some limitations too during execution in the aspects of both management and technology. Recycled aggregates account for 6%-8% of aggregate use in Europe with differences between countries (Aslani et al., 2018). It is well known that aggregates are the major constituents of concrete, it is important to choose them properly in order to achieve concrete development innovation. Essentially, proper aggregate selection and size distribution manipulation are critical steps in the production of all types of concrete.

1.2. Research general objectives

The main objective is to determine the influence of three types of recycled aggregates (ceramic, mixed and concrete) in 60% of replacement of 0/4 mm natural sand in the improvement of high-performance self-compacting concrete properties produced with different type of binders (binders with 0%, 30% and 50% of Fly Ash). The fresh and hardened properties have been assessed.

1.3. Research specific objectives

The following particular objectives have to be met in order to achieve the study's main objective:

- The influence of three types of recycled aggregates in the fresh properties of concrete (slump, V-Funnel and L-Box tests).
- The influence of three types of recycled aggregates in the physical al mechanical properties of concrete produced with 0%, 30% and 50% of Fly Ash
- Determination of the feasibility of recycled fine aggregates as internal curing agent, by analyzing the autogenous shrinkage.
- The ability of this type of concrete to continue to perform its intended function, which maintained its required strength, serviceability and durability (analyzing the drying shrinkage and chloride diffusion) to withstand external environmental agents during the service life.

1.4. Structure of the thesis

This thesis is divided into 5 chapters, each chapter has for aim the analysis of a specific section of the work.

a) Chapter 1: Introduction

In the 1st chapter, the topic is introduced and presented, as well as the main and specific objectives of this study. Also, a brief description of the project structure.

b) Chapter 2: State of the art

The 2nd chapter includes a thorough literature review on the subject. Supportive literature has been used throughout this section to discuss what has been done in relation to the topic.

c) Chapter 3: Experimental process

The study's objectives established the framework within which all experiments would be carried out in order to attain the research's principal goal. The material properties were determined and the results collated so that they could be used in the data analysis part that followed. Both the fresh and hardened concrete tests were carried out in order to understand this concrete performance. All the tests were conducted in the Laboratory of Technology of Structures and Materials "Lluis Agulló" of the UPC with modern equipment, ensuring highest performance.

d) Chapter 4: Results and analysis

This part incorporates all of the data gathered throughout the experimental phase, which included comprehensive analysis in order to determine the best performance of this type of concrete. All the results of the different tests conducted are analyzed and compared with the behavior of conventional concrete, with the help of analytical tools like graphs and tables and with previous researches.

e) Chapter 5: Conclusions

In this chapter, the obtained conclusions of this study are presented and some suggestions for future researches.

2. Chapter 2: State of the art

2.1. Definitions

2.1.1. *Self-Compacting Concrete (SCC)*

According to the European Guidelines for Self-Compacting Concrete(EFNARC & The European Project Group, 2005), it is a concrete that is able to flow under its own weight and completely fill the formwork, even in the presence of dense reinforcement, without the need of any vibration, whilst maintaining homogeneity

2.1.2. *High-performance concrete (HPC)*

According to (Islam Laskar, 2011), high strength, high durability, and high workability are three features of high-performance concrete. HPC demands a dense, void-free mass in full contact with reinforcing bars, and the workability must be compatible with these basic requirements; moreover, the mix proportioning should be such that permeability is as low as feasible for the specific application (Islam Laskar, 2011).

2.2. Self-compacting concrete

Self-compacting concrete (SCC) has steadily gained favor in recent decades as a result of its unique ability to fill formworks with congested steel reinforcement while requiring little or no mechanical compaction. It was initially developed in 1988 in Japan with the purpose of creating long-lasting concrete structures, since then, other studies have been conducted and the concrete has been utilized in real-world constructions in Japan and then in other countries (Okamura, H; Ouchi, 2003). There is an increasing demand from the construction industry to adopt new processes in its production, in this regard, the mixture components and their proportion would be crucial parameters. Workability of the fresh concrete, strength and durability of the hardened concrete are the main interests in developing new concrete types. The source and type of constituent materials, as well as their properties and how they'll be mixed, are all the elements that influence the properties of this concrete; because individual constituents have a stronger influence on SCC than on conventional concrete, these constituents should be carefully chosen (Khaleel & Abdul Razak, 2014). For SCC, many mix design approaches have been proposed, by optimizing normal concrete ingredients with a superplasticizer and a viscosity-modifying agent (VMA)(Celik et al., 2014).Using high volume of supplementary cementing materials such as fly ash provides a sustainable solution. SCC is a very sensitive material and its rheological properties change with little change in material properties, mix compositions, and so on. Normally compacted concrete (NCC) and SCC consist of the same constituents, but there is a clear difference in their mix composition and fresh properties.

Over the past few decades, many researchers have explored ways of overcoming the drawbacks of conventional vibrated concretes. The majority of work done in this field is related to changing the constituents of the vibrated concrete to improve the interfacial bond between the mortar matrix and aggregates. High Performance Self-Compacting Concrete (HPSCC) is a solution to enhance the workability requirements of fresh concrete with high strength and durability. HPSCC refers to advanced cementitious composite material whose mechanical and durability properties are higher than those of normal conventional concrete. In order to produce a HPC some modifications need to be made to both the mixing and curing processes. The benefits of using HPCs are compaction without segregation, higher tensile capacity, toughness, early age strength, high compressive strength, etc.

The mixture of SCC is strongly dependent on the composition and characteristics of its constituents in the fresh state. The properties of SCC in its fresh state have a great effect on its properties in the hardened state. Therefore, it is critical to understand its flow behavior in the fresh state. As the SCC defined in terms of its flow-ability, the characterisation and control of its rheology is crucial for its successful production.

Recommendations on the design and applications of SCC in construction have now been developed by many professional societies, including the American Concrete Institute (ACI), the American Society for Testing and Materials (ASTM), Center for Advanced Cement-Based Materials (ACBM), Precast Consulting Services (PCI) and Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages (RILEM) etc.

Some of the advantages and disadvantages of SCC concretes are described below (Shi et al. 2015):

Advantages

SCC has many advantages over conventional concrete, including:

(1) Eliminating the need for vibration.
(2) Decreasing the construction time and labor cost.
(3) Reducing the noise pollution.
(4) Improving the filling capacity of highly congested structural members.

(5) Improving the interfacial transitional zone between cement paste and aggregate or reinforcement.
(6) Decreasing the permeability and improving the durability of concrete, and
(7) Facilitating constructability and ensuring good structural performance.

Disadvantages

(1) SCC requires higher powder and admixture (particularly super plasticizers) contents than Normal Concrete and so the material cost is higher. The cost increase range from 20% to 60% compared to similar grade Normal Concrete.
(2) The increased content of powder and admixture also leads to higher sensitivity (i.e. reduced robustness) of SCC to material variation than that of NC; thus, greater care with quality control is required.

2.2.1. Materials

SCC has the same constituent materials as those for Normal Concrete (NCC) but their relative proportions differ and need to be carefully selected. Lower coarse aggregate content and higher amounts of cement and admixtures (particularly super plasticizers) are required to achieve self-compacting properties. The materials suitable for NCC can be used to produce SCC, but they affect the fresh properties of SCC.

Binder/Powder

SCC performance is highly dependent upon the properties of the cementitious materials due to its larger content. Suitable cementitious materials are selected depending on the type of structure, the characteristics of the aggregates, material availability, and method of construction. It is more important to use the proper powder(s) to achieve the required fresh and hardened properties of concrete. Powders are the smallest solid particles in concrete, and include cement and additions. Aggregates in SCC mainly affect blocking, whereas powder particles fill the voids between aggregates and affect the friction and collision between aggregates. The packing of the powder particles themselves is thus important for SCC, which depends on the shape, size and surface characteristics of the particles and their behaviour during mixing.

Cement

Concrete can be made with any cement that meets the European Cement Standard EN 197-1. However, depending on the application, differences in cement type may need to be considered in order to assure the long-term durability of concretes produced with these cements. The C3A and C4AF content affect consistence retention due to their initial rapid hydration (Celik et al., 2014). That is why cements with low C3A and C4AF were preferred in the early development of SCC in Japan.

Cement is a critical component in any concrete mix, affecting the majority of the mix properties such as: workability, compressive strength, drying shrinkage and durability. Cement particles react with water during hydration process, binding the aggregate and forming the strength matrix. This hardening process lasts for years, resulting in concrete that becomes stronger with age.

In the production of high-performance concrete, the type of cement used is very crucial. There exists different types of cement, type I, II, II, and IV, each with its distinct characteristics. The cement used in this type of concrete should have a high mechanical strength and low tri-calcium aluminate C3A because this latter causes cement to become incompatible with a superplasticizer, moreover, the rheology of cement having low C3A can be easily controlled.

Supplementary Cementitious Materials (SCM)-Fly Ash

Supplementary cementitious materials (SCM) are a diverse group of materials with a variety of chemical compositions, mineralogies and physical properties. Different mineral admixtures like Fly ash, limestone powder, silica fume etc. are used as Supplementary Cementitious Materials in SCC. SCMs are commonly utilized in concrete, either as part of blended cements or as a separate ingredient in the concrete mixer.

Two Fly Ash classes are defined by ASTM, Class C and Class F, during this research Class F fly ash is used. In Class F fly ash, total calcium typically ranges from 1 to 12%, mostly in the form of calcium hydroxide, calcium sulphate and glassy components, in combination with silica and alumina, also, the amount of alkalis and sulphates are lower compared with Class C fly ash (Ahmaruzzaman, 2010).

Fly Ash

In this research, Fly Ash was used as a SCM. Fly Ash are one of the residues produced by coal combustion for the production of heat and electricity and they are caught by electrostatic precipitators, or bag fillers, before the flue gases are released (Giergiczny, 2019). Because (i) the reactivity of fly ash is very limited and (ii) the CaO in the fly ash represents an additional source of calcium, mixing Portland cement with fly ash results in a reduction in the total amount of portlandite in the hydrated mixture, which is slightly less pronounced than for silica fume (Lothenbach et al., 2011)

Classification

As per ASTM fly ash is classified into Class F and class C.

Class F fly ashes are low in CaO, the fly ash obtained from burning anthracite or bituminous coal falls in this category. This class of fly ash exhibits pozzolanic property but rarely, if any, self-compacting property. They are predominantly (70%) non-crystalline silica, which is the determining factor for pozzolanic activity. Their Crystalline minerals are generally composed of quartz, hematite, illite and magnetite.

Class C fly ashes are produced from lignite or subbituminous coal. This class of fly ash has both pozzolanic and varying degree of self-cementitious properties. (Mostly class C fly ashes contains more than 15% CaO but some class C fly ashes may contain as little as 10% CaO).

Fly Ash in concrete

- Reduction in amount of coal combustion products that must be disposed in landfills, and conservation of other natural resources.
- Reduction in energy use, greenhouse gas (CO2) and other adverse air emissions when fly ash is used to replace manufactured cement.
- Workability and rheological properties of fresh SCC improved with FA (Devi et al., 2019). The uses of fly ash improved the workability and durability, prevents thermal cracking and alkali–aggregates reaction.
- Fly ash in concrete produces dense and smooth surfaces with sharper details
- Increasing the life of concrete roads and structures by improving concrete durability.

Natural aggregates

Natural aggregates are developed by natural actions, they comprise both sand and gravel, besides water and Portland cement, aggregates are an essential component of concrete. Aggregates split into two categories: fine and coarse, depending on the size of the particles. They make up 60 to 75 percent of the entire volume of concrete with a significant impact on the fresh and hardened properties of concrete as well as on the mixture proportions and economy. As a result, selecting aggregates is a critical step. Although some variability in aggregate properties is to be expected, some criteria should be taken into account such as, the grading, the durability, the particle shape and texture and the absorption capacity. Aggregate grading is the process of determining the particle size distribution, grading restrictions and maximum aggregate size are defined since these properties influence the amount of aggregate used, as well as the amount of cement and water required. Because aggregate's internal structure is made up of solid material and voids that may or may not hold water, absorption and moisture content are evaluated while selecting aggregate. The amount of water in the concrete must be modulated to account for the aggregate moisture conditions.

Fine Aggregate

The influence of fine aggregates on the fresh properties of the SCC is significantly greater than that of coarse aggregate. The fine aggregate used in SCC is natural sand with a uniform grade and with particle size less than 0.125mm paste and should take into account in calculating the water powder ratio. Sands with well-distributed grading, spherical shape and low absorption are advantageous to SCC. Consequently, the naturally rounded cleaner sand might be preferable to angular crushed sand. The moisture in the sand effects SCC, it is therefore important to monitor the moisture content of the fine aggregates. The optimum volume content of fine aggregate in the mortar varies between 40 to 50%, in order to eliminate direct interlocking of fine aggregate particles.

Coarse Aggregate

It is believed that a continuous grading of aggregates, which results in a better deformation capacity, is better suited for SCC. Well-graded aggregates either round or cubical shapes are a best choice. In fact, a wide range of aggregate types, sizes and shapes has been used in SCC; the size of the aggregates used for SCC design is limited to 20mm. If the reinforcement employed for the structure is congested, the aggregate size used can be in the range 10 to 12mm. Although packing does not have much influence on the final strength, it has a major effect on the fresh properties of a concrete. A combination of fine and coarse aggregates and graded aggregates increases the packing density, which leads to a reduced superplasticizer dosage and paste volume. This also helps segregation resistance because small aggregates can resist the settlement of medium size aggregates, which in turn will resist the settlement of large aggregates. To minimize the interaction between the aggregates, particle shape is also important. Naturally, rounded gravel might be preferable to angular crushed aggregate for SCC. Natural gravels will give a better filling ability because of the smaller inter-particle friction but crushed aggregate has a beneficial effect on the strength of concrete. Therefore, the fineness, shape, distribution, packing density and ratio of sand/coarse aggregates all have influence on fresh properties of SCC.

Recycled aggregates

Recycled aggregates are created from the reprocessing of materials that were previously used in construction. Sand, gravel and crushed stone are among them. To guarantee that the aggregates meet legal criteria, a reprocessing process involving crushing and mixing is required. The fresh and hardened properties of recycled aggregate concrete depend on the properties of the original material from where the RA is derived, the w/c ratio, the size of recycled aggregates, etc… When compared to natural aggregates, recycled aggregates have a lower density, a larger water absorption capacity, and a lower mechanical strength; they are also quite heterogeneous and porous and they can contain a lot of contaminants, lowering the quality of concrete with them (Etxeberria, 2020). Moreover, it was found that this type of aggregate can reduce the autogenous shrinkage by one-half of the original OPC concrete (Lee et al., 2018). There exists different types of recycled aggregates. The recycled ceramic and mixed aggregates have a higher water absorption capacity compared with recycled concrete aggregates, however, the three types of RAs can make it difficult to control the effective water-cement ratio, reducing workability of new concrete and influencing the strength and durability of hardened concrete as a result (Etxeberria, 2020). According to (Huang & Zhao, 2009), the characteristics of RA vary greatly, owing to their numerous potential compositions, although not solely. Concrete created using concrete aggregates, for example, has different characteristics than concrete made with ceramic aggregates, and the latter is predicted to perform worse in theory. The grading curve, density, and water absorption of the aggregates are among the factors that impact the mechanical characteristics and durability of concrete, in addition to composition (Huang & Zhao, 2009).

Recycled ceramic aggregates

According to (Etxeberria, 2020), ceramic waste generated by ceramic manufacturers during the manufacturing process can also be found in the demolition of existing structures. Unfortunately, because this waste is frequently mixed with waste from other inorganic materials that have a negative impact on their properties, mixed RAs with worse technical properties arise. Only a few research have looked at the usage of recycled ceramic aggregates in HPC. They cited the difference in water absorption between ceramic and natural aggregates as the primary impediment to using ceramic aggregates in the manufacture of concrete that loses strength, workability, or durability (Etxeberria, 2020).

Recycled concrete aggregates

Recycled concrete aggregates have an attached residual mortar that contains hydrates and an all interfacial zone (ITZ) (between the mortar and the original aggregate), making it porous and very absorbent. Because RCA has a high absorption rate and absorbs more water during mixing, it acts as a natural moisture reservoir, assisting in the ongoing hydration of cement (Etxeberria, 2020).

Recycled mixed aggregates

Crushed and graded concrete and masonry debris make up recycled mixed aggregates, the resulting aggregate is a mixture of two main components: concrete and ceramic. Due to the great diversity in recycled mixed aggregates, their use is restricted (Etxeberria, 2020) .

Chemical Admixtures

An admixture is a material added in small quantities during mixing to modify the properties of the concrete mixture. The demand for a high-level of workability, together with good stability of the mix for SCC has led to the use of a number of admixtures. There are many admixtures that have been reported as used in SCC, but superplasticizers are the essential ingredients. It is designed to improve rheology and thus its workability. It has many properties including, great water reducing power, improvement of the finish and texture of the concrete surface, it increases the initial and final strength of concrete and it reduces application time and compaction. Interaction between Portland cement and admixture affects fluidity, setting and stiffness of cement paste.

Water

Water has profound effects on both the fresh and the hardened properties of SCC. Water decreases both the yield stress and the plastic viscosity. Concrete is much more prone to segregation if only water is added to increase the filling ability. Because of this, SCC could not have been developed until suitable superplasticizers were produced. Water in the fresh concrete includes freely movable water and the water retained by the powder (additions and cement), sand and VMA. Coarse aggregate does not confine water. It is the free water that controls the performance of SCC. Free water is one of the main factors determining the filling ability and segregation resistance. Free water content was used to predict slump flow and T500 with satisfactory accuracy in a deformability model. The moisture content of the aggregate has a significant effect on free water content. The moisture variation in sand of 3~4% led to a W/C ratio variation of ±0.1. It is therefore important to correctly estimate the aggregate's moisture content.

2.2.2. Mix design

Concrete mixture design is a selection of raw materials in optimum proportions to give concrete with required properties in fresh and hardened states for particular applications. Different from conventional concrete, a quality SCC should have three key properties, filling ability, passing ability and segregation resistance. Based on EHE-08-Annex 17 the Spanish standard, the overall fine content (particle size<0.125 mm), i.e. cement, additives, and fillers, in a self-compacting concrete should be in the range of 450 to 600 kg/m3 (180 to 240 liters/m3). The cement content varies between 250 and 500 kg/m3. The volume of the paste (water, cement, active mineral additives, fillers, and admixtures) is usually greater than 350 liters per m3. Given that the paste is primarily responsible for aggregate fluidity and movement, it helps justify continuous granulometry and, in addition to the spacing criteria between bars, a maximum aggregate size of 25 mm. Self-compacting concrete has a smaller coarse aggregate volume than conventional concrete, often not surpassing 50% of total aggregates.

In general, designing conservatively ensures that the concrete can keep its stated fresh characteristics despite expected changes in raw material quality. At the mix design stage, some fluctuation in aggregate moisture content should be anticipated and accommodated. Adjustments to the mix composition should be made if necessary. The mix should be tested once all conditions have been met.

According to EFNARC guidelines (EFNARC, 2002), if adequate results are not achieved, a fundamental redesign of the mix should be considered. The following actions may be suitable depending on the perceived problem:

- utilizing extra or other types of filler (if available)
- adjusting the sand or coarse aggregate quantities;
- if a viscosity modifying agent isn't already in the mix, using one;
- altering the amount of superplasticizer and/or viscosity modifying chemical used;
- utilizing alternative superplasticizers (and/or VMA) that are more compatible with local materials;

- changing the admixture dosage to change the water content and therefore the water/powder ratio.

Based on the design principles, the SCC mix designs can be classified into five categories (Shi et al. 2015)

(1) Empirical design method.
(2) Strength based design method.
(3) Close aggregate packing method.
(4) Statistical factorial model.
(5) Rheology of paste model.

The empirical design method is employed based on the EFNARC guidelines for mix proportions and required fresh properties.

2.2.3. Fresh properties

In contrast to conventional concrete, SCC's fresh properties are critical in determining whether it can be properly placed. To guarantee that its ability to be placed stays acceptable, the many components of workability that affect its Filling ability, Passing ability and Segregation resistance must all be properly regulated.

Filling ability

According to EFNARC guidelines (EFNARC, 2002), Filling ability is the ability of SCC to flow into and fill completely all spaces within the formwork under its own weight. By utilizing a superplasticizer and lowering the coarse aggregate content, it is possible to obtain high flowing ability by reducing inter-particle friction among solid particles (coarse aggregates, sand and powder) in concrete. In fact, the ability to flow is influenced by the particle size distribution; inter-particle friction can be decreased by using continuously graded materials (EFNARC, 2002). Deformability covers two aspects: deformation capacity and deformation velocity. Deformation capacity refers to the maximum ability to deform or how far concrete can flow, while deformation velocity refers to the time it takes for concrete to finish flowing, or how quickly concrete can flow. The test achieved in order to check the Filling ability is the Slump Flow test (EFNARC, 2002)

Passing ability

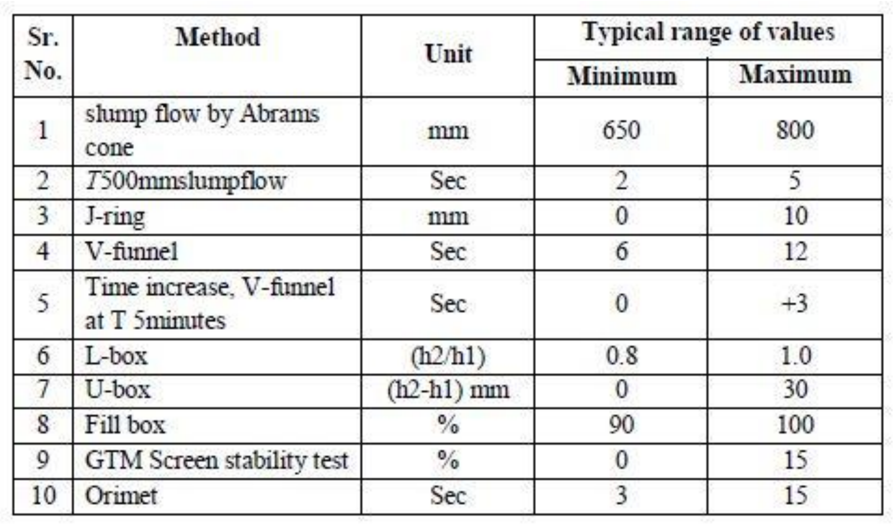
As defined in the EFNARC guidelines, the Passing ability or confined flowability is the ability of SCC to flow through tight openings such as spaces between steel reinforcing bars without segregation or blocking. The geometry and the density of the reinforcement, the flowability/filling ability and the maximum aggregate size must all be considered when determining the passing ability (EFNARC, 2002). The smallest space (confinement gap) through which SCC must continually flow to fill the formwork is the defining dimension. The reinforcement spacing is frequently, but not always connected to this gap. This space between reinforcement and formwork cover is typically not taken into account unless the reinforcement is extremely congested, as SCC can surround the bars and does not need to flow continually through these spaces. The passing ability of SCC is checked through L-box, U-box, Fill-box and J-ring test methods (EFNARC, 2002).

Segregation resistance

The Segregation resistance is the ability of SCC to remain homogenous in composition during transport and placing (EFNARC, 2002). The possibility of segregation and blockage is quite significant in SCC due to its high fluidity. As a result, preventing segregation is an important aspect of the control regime. Static and dynamic segregation are the two types of segregation. When the concrete is at rest before setting, the cement paste and coarse aggregate tend to separate vertically, this is known as static segregation. In the presence of flow, this separation also occurs horizontally, which is referred to as dynamic segregation. Poor segregation resistance can cause an uneven distribution of coarse aggregate, blocking of flow around reinforcement, high drying shrinkage and non-uniform compressive strength (Bui et al., 2002). By applying a sufficient amount of fines (<0.125mm) or a Viscosity Modifying Admixture (VMA), the tendency to segregate can be decreased. Because there is currently no easy and reliable test that delivers information regarding SCC segregation resistance in all practical settings, extra caution should always be taken to ensure the mix does not segregate. However, some tests will show the segregation resistance of SCC, namely, the V-Funnel test and the GTM Screen stability test (EFNARC, 2002).

Table 1 shows typical approval requirements for SCC with a maximum aggregate size of 20 mm (EFNARC, 2002).

Table 1. Acceptance criteria for self-compacting concrete.



Sr. No.	Method	Unit	Typical range of values	
			Minimum	Maximum
1	slump flow by Abrams cone	mm	650	800
2	*T*500mmslumpflow	Sec	2	5
3	J-ring	mm	0	10
4	V-funnel	Sec	6	12
5	Time increase, V-funnel at T 5minutes	Sec	0	+3
6	L-box	(h2/h1)	0.8	1.0
7	U-box	(h2-h1) mm	0	30
8	Fill box	%	90	100
9	GTM Screen stability test	%	0	15
10	Orimet	Sec	3	15

These conditions must be met at the time of order placement. Changes in workability that may occur during transportation should be factored into the manufacturing process. These usual requirements, which are displayed next to each test technique, are based on current knowledge and experience. Future advancements, on the other hand, may lead to the adoption of new requirements. Because there is currently no easy and accurate test that offers information regarding SCC segregation resistance in all practical scenarios, extra caution should always be taken to guarantee that the mix does not segregate.

2.3. Binary mix proportion with fly ash and superplasticizer

2.3.1. Mix proportions

Generally the concrete mixtures were designed based on a control mixture included only ordinary Portland cement (PC) as the binder while the remaining mixtures incorporated binary (PC + FA) cementitious blends in which a proportion of Portland cement was replaced with the mineral admixture FA up to 60%.

Several researchers produced high performance SSC (with minimum 50MPa) of compressive strength employing high amount of fly ash (Celik et al., 2014) (P. R. Da Silva & De Brito, 2015). Following the EFNARC Guidelines, all the described mixtures fulfil the requirement of employing the cement amount of 350 to 450 kg/m3, except the works carried out by Silva and de Brito (P. R. Da Silva & De Brito, 2015). In the first mentioned paper (Celik et al., 2014), the cement amount exceeded when 30% of FA was employed. In the second paper mentioned (P. R. Da Silva & De Brito, 2015), all the mixtures exceeded the maximum cement amount defined by EFNARC. With respect to The guideline of Total powder content 400-600 Kg /m3 defined by EFNARC, all the mixtures fulfilled it, except two of the three mixtures defined by da Silva and de Brito works (Pedro Raposeiro da Silva & de Brito, 2016). The EFNARC Guidelines also defined the adequate mix proportions of mortar volume mortar (>40%), paste volume (<50%) and total mass of aggregates (>50%). According to mass of aggregates and paste volume of the concrete, all the mix proportions defined in Table achieved the EFNARC requierements , except the mixtures defined by Silva and de Brito (P. R. Da Silva & De Brito, 2015) in which the total mass of aggregates was also higher than 50%, however the paste volume was higher than 50% of the concrete volume. A higher amount of powder used, the aggregates amount was reduced. The mixtures which employed the mass of aggregates between 60-70% of the concrete mass were those that employed higher amount of powder for concrete production Silva and de Brito (P. R. Da Silva & De Brito, 2015). Few of the researchers employed the mass of aggregates between 75-80%, (Celik et al., 2014). In order to achieve a high strength, in the cases a maximum of Dmax of 16 mm or 12.5mm were used for concrete production. All the mixtures described used polycarboxylic high-range water-reducing admixture in order to achieve adequate fresh state properties.

2.3.2. Fresh properties

Slump Flow and T50

According to the slump flow results, all mixes produced with blended cement with fly ash met the specified SCC flow requirements.(Celik et al., 2014) (P. R. Da Silva & De Brito, 2015) .It could be seen that increasing amount of FA had the effect of either decreasing the water reducer content or T50 in binary mixes in order to achieve the same flowability. The slump flow increased with the addition of fly ash to the mixtures.

The control mixture (without FA) had the highest SP content, but as part of the PC was replaced by FA, the SP content of mixtures decreased. Similar workability properties were achieved in FA mixtures to Conventional SSC concrete by using a lower SP content, this was also probably due to the spherical shape and smooth texture of the fly ashes, which can promote a bearing effect and reduce the friction between the particles of the mixtures (Celik et al., 2014) (P. R. Da Silva & De Brito, 2015).

When analysing these parameters the following aspects are taken into account: W/C ratio of the mixes, influence of the Sp content, influence of the aggregate size and maximum fly ash replacement ratio.

V-Funnel

Incorporating FA replacement decreased the viscosity which in turn resulted in lower V-funnel flow time of the concretes. The time using the V-funnel measured by certain researchers (P. R. Da Silva & De Brito, 2015) was in the range of EFNARC standards. Higher V-funnel flow time values observed for lower W/C ratios. In most of studies found that the V-funnel flow time is higher in the control mix and decreased with FA incorporation.

L-Box

The L- Box values are in the range of acceptance criteria for test on fresh SCC as per EFNARC.(P. R. Da Silva & De Brito, 2015). The replacement of cement with fly ash improved the passing ability of the SCCs i.e., increased the H2/H1 ratio. The increase in the paste content, in addition to the bearing effect from the spherical particles of the fly ash can explain this improvement. All SCCs defined by those researchers were classified as PA2 (H2/H1 > 0.80 with 3 bars) according to EFNARC. SCCs containing 40-60% replacement presented H2/H1 ratios higher than 0.90. This indicates that cement replacement by the fly ashes improved the passing ability of the SCCs.

2.3.3. Mechanical and Durability properties

The binary use of PC + FA reduced compressive strength of SCCs with increasing the replacement level of FA for 28 days compared to the reference mixture but, subsequently increased 91 and 182 days strength. (Celik et al., 2014) (P. R. Da Silva & De Brito, 2015) .These researchers achieved a compressive strength higher than 50MPa at 28 days employing up to 40% of FA in replacement of Portland cement (Celik et al., 2014) (P. R. Da Silva & De Brito, 2015) .They found that replacing cement with 20% and 30% fly ash has no significant effects on hardened concrete properties. Higher replacement levels led to a reduction in the compressive strength. In addition, according to Da Silva and de Brito (P. R. Da Silva & De Brito, 2015) the mixture produced employing 60% of FA could achieved a higher strength than 50MPA when they were produced employing 600 kg of binder (with 290 kg of cement) and a water-binder ratio of 0.30.

W/C ratio has a significant influence on the water absorption because, concrete’s porosity increases with the W/C ratio, i.e. the higher the W/C ratio the greater the volume of the cement matrix’s pores, thereby increasing the volume of accessible pores. (P. R. Da Silva & De Brito, 2015).

All the binary mixes made with blended cements with FA demonstrated higher resistance to the chloride migration compared to the control mixes. This increased resistance to chloride penetration due to the incorporation of FA may result from the chloride ions passage by diffusion being more difficult or even blocked, since the rounder FA particles contribute significantly to the improved capacity both of the SCC paste matrix and around the coarser aggregates (Celik et al., 2014).

The optimal performance of the mixes are with FA between 30% and 60%(P. R. Da Silva & De Brito, 2015).

2.4. Concrete with recycled fine aggregates

Previous researches are discussed on this section analyzing the behavior including the fresh and hardened properties of concrete while integrating recycled aggregates into the mix.

2.4.1. Fresh properties:

Zega et al. (2011) fixed the replacement of recycled fine aggregates to 20% and 30%, it was found that although the admixture dose was increased, the consistency of RC20 concrete was equal conventional concrete, but the slump of RC30 concrete was substantially reduced because RFA was used in an air-dry state, a portion of the mixing water was absorbed with the additive and as a result of the increased RFA concentration in RC30 concrete, this effect is more pronounced on the concrete's fresh state characteristics (Zega et al., 2011)**.** Behera et al. (2019) found that by keeping the powder content constant, the desired flow could be attained for all SCC mixtures depending on three independent factors (water absorption kinetics, SP, and VMA dose). The use of RFA has a positive impact on SCC's flowability and filling ability, It did, however, have a detrimental impact on passing ability. In addition, the usage of RFA in SCC fails to fulfill the blocking evaluation between slump and J-ring flow. With time, the rise in RFA concentration has a substantial impact on the flow retainability of SCC mixtures (Behera et al., 2019). On the other hand, Kapoor et al. affirm that when NA were replaced with RA, T500 time increased since RA in SCC mixtures increases viscosity due to their porous nature, but this was kept below acceptable limits by adding VMA in SCC mixes, also V-funnel flow time increased by 54% due to a 100% replacement of RCA and RFA in the SCC mixture and similarly there is no discernible influence on the L-box ratio when RCA is completely replaced in the SCC mixture (Kapoor et al., 2020).

2.4.2. Physical properties:

When comparing a reference concrete produced entirely of NFA to a concrete made entirely of RFA, water absorption by immersion rises with the replacement ratio of NFA by RFA, reaching a maximum of 46% for concrete made entirely of FRA, water absorption appears to rise linearly with replacement ratio; this is to be anticipated, given that FRA have a more porous structure that extends into the concrete matrix (Evangelista & Brito, 2010). Ben Nakhi et al. (2019) stated that recycled aggregate mixtures have lower bulk densities than natural aggregate, but they have higher moisture content and water absorption. (Ben Nakhi & Alhumoud, 2019). Similar conclusion was deduced by Etxeberria (2014) that affirmed that in comparison to traditional concrete, using up to 50% fine ceramic or mixed recycled aggregates as a substitute for natural sand resulted in a density loss of less than 5%, however, absorption increased by more than 40% (Etxeberria, 2014). Given RA's lower density relative to NA's, it appears that density dropped with its inclusion, The 100 %RA mix had the greatest density decrease (5% loss from the reference SCC) (Barroqueiro & Silva, 2019).

2.4.3. Hardened properties:

2.4.3.1.Compressive strength:

Zega et al. (2011) found that concretes with 20% and 30% recycled fine aggregate have compressive strengths comparable to concrete containing 100% natural fine aggregate and this can be explained by the fact that RC concretes have a lower effective water/cement ratio than CC concretes. (Zega et al., 2011). However (Etxeberria, 2014) stated that fine recycled aggregates concrete has lower early-age compressive strength than ordinary concrete and after 28 days of curing, all of the concretes made with up to 50% fine RAs had a greater strength than ordinary concrete (Etxeberria, 2014). When compared to the reference conventional concrete after 28 days, the concrete containing 100% recycled aggregates had a 47% loss in compression strength (Carro-lópez et al., 2015). Zhao et al. mentioned that or the three distinct W/C ratios examined, mortars built with dried RFA had higher compressive strengths than those created with saturated aggregates. The ITZ between the cement paste and saturated FRCA is greater than the ITZ between the cement paste and dry RFA, the absorption of water by the cement paste included in RFA improves the thickness of ITZ and therefore its characteristics (Zhao et al., 2015). The 28-day compressive strength increases due to the superplasticizer were larger for the control mix than for the RFA mix, and the effect of SP decreased as the RFA concentration increased (Pereira et al., 2012) (Cartuxo et al., 2015). Kappor et al. (2020) stated that due to the presence of old ITZ in the concrete matrix, compression strength diminishes when RA (both coarse and fine) is substituted in SCC mixes (Kapoor et al., 2020).

2.4.3.2.Tensile strength and elastic modulus:

With a rise in the replacement ratio, both tensile splitting and modulus of elasticity are lowered; nevertheless, the values obtained for both properties are still acceptable, especially at appropriate replacement ratio levels (30%) (Evangelista & Brito, 2007) (Zhao et al., 2015). Etxeberria (2014) found that he RA concretes had similar values for splitting tensile strength and modulus of elasticity to ordinary concrete (Etxeberria, 2014). In comparison to the other concretes, the 30 percent replacement RFA concrete has a small drop (7%) in splitting tensile strength. Furthermore, the static modulus of elasticity of this concrete is 7% lower than the conventional concrete modulus. This is due to the fact that RC30 concrete has a lower compressive strength (Zega et al., 2011). Also, from the literature, it was observed that there is an increase in tensile strength when RA are added to the mixture (Aslani et al., 2018). And no significant change was observed in the work of Ju et al. (Ju et al., 2019) when RA were added in concrete, it was noticed that the amount of RFA did not affect the tensile strength dramatically, especially when the curing time was sufficient.

2.4.3.3.Shrinkage:

The main factors that influence the autogenous shrinkage of concrete are w/c ratio and concrete maturity, the latter is mainly influenced by ambient temperature and the type of cement and autogenous shrinkage contributes significantly to concrete cracking when the w/c ratio is less than 0.43 (Jianxia, 2012). It was shown by Lee et al. (Lee et al., 2018) that autogenous shrinkage can be reduced by the use of recycled aggregates through their internal curing effect.

According to Yildirim et al. (Yildirim et al., 2015), the incorporation of recycled aggregates decrease the drying shrinkage because of the long-term effects of the internal curing.

The drying shrinkage of conventional concrete and 20% RFA concretes after 180 days is identical due to the same mixing water content utilized in both concretes, while the 30% RFA concrete has a significantly lower drying shrinkage strain due to the lower w/c ratio (Zega et al., 2011).

(Li et al., 2020) utilized saturated concrete RFA in mortar and noticed a reduction in early age autogenous shrinkage, as well as RFAs with smaller particle sizes and better water absorption capabilities, which may be ascribed to the RFA pore structure.

According to (Etxeberria & Gonzalez-Corominas, 2018), the autogenous shrinkage of such concretes was lower than that of CC concrete, and it was almost non-existent in concretes made with 30% FCA (aggregates with 12% of water absorption capacity) and despite the early drying shrinkage of recycled aggregate concretes was up to 125 percent greater than that of CC concrete after 7 days of testing, the shrinkage was decreased after a longer period of testing and the mass of water lost was always less than the amount of water absorbed by the recycled aggregates (at the time of concrete manufacture), ensuring that the concretes would behave properly (Etxeberria & Gonzalez-Corominas, 2018).

Kirthika et al. (2020) expressed that due to the old attached paste, RFA concrete was discovered to have increased shrinkage at the beginning of its life. Later ages saw the rate of shrinkage slow down because to the establishment of dense microstructure and a reduction in voids. The drying shrinkage values increase as the RFA content rises. This is due to the presence of particles, dust, or un-hydrated cement paste, which requires additional water. (Kirthika & Singh, 2020).

Because of its internal curing effect, the inclusion of RA can reduce the autogenous shrinkage of RA concrete. Autogenous shrinkage is influenced by the composition and properties of RA concrete (saturation degree, particle size, and source) and the drying shrinkage increased with the increasing of replacement ratio of RA (Mao et al., 2021).

Ju et al. (2019) affirmed that the drying shrinkage strain of RFA concrete increased as the replacement content increases, and it was greater than that of conventional concrete. This could be because, due to RFA's increased water absorption, a higher RFA replacement ratio results in more water in concrete. (Ju et al., 2019).

2.4.3.4.Chloride resistance :

According to (Evangelista & Brito, 2010) when comparing the concrete with total replacement to the reference concrete with no RFA, the non-steady-state chloride migration coefficient increases linearly with the replacement ratio of fine aggregates, reaching a maximum of 34%.

Etxeberria (2014) found that at one year, the chloride resistance of concrete containing up to 50% ceramic or mixed fine RAs was comparable to or better than that of standard concrete. The inclusion of ceramic fine grains reduced chloride ion penetrability in the concretes (Etxeberria, 2014).

The rate of chloride penetration into the concrete was found to be proportional to the volume fraction of RFA, with the penetration rate increasing as the RFA concentration rose. At 28 days, RFA 30 had a 21.25% stronger resistance to chloride penetration than control concrete, whereas

RFA100 had nearly twice the value of penetration as control concrete. This is due to RFA containing more free water than control concrete, leading in a porous microstructure (Kirthika & Singh, 2020).

2.5. Internal curing

Internal curing is described as the provision of water inside concrete in place of or in addition to the typically utilized external water spraying to achieve curing internally. Generally, internal curing reduces water consumption, improves concrete homogeneity and reduces surface cracking in general (El-Hawary & Al-Sulily, 2020). Internal curing has a number of advantages in various concrete mixtures. Reduced plastic, autogenous, and drying shrinkage (and associates cracking), increased hydration in rich mixtures, improved late-age compressive strength and reduced concrete transport characteristics are only a few of the advantages (Bentz & Weiss, 2011). Internal curing not only prevents the cement paste from drying out, but it also keeps it hydrated. In addition, the rough texture of an internal curing water reservoirs (ICWR) can enhance the paste–aggregate connection (Al Saffar et al., 2019) (Ma et al., 2019) (Lura et al., 2007) which some writers refer to as the "nailing effect" (R. V. Silva et al., 2015). The ICWR's weakness, on the other hand, might negate these positive benefits (Bremner & Holm, 1986). As a result, internal tension caused by various processes (such as drying and self-desiccation) can cause greater deformations in internally cured concrete (Lura et al., 2007) ,which is in direct opposition to the goal of internal curing. However, it has been suggested that a lower modulus of elasticity reduces the cracking potential (R. V. Silva et al., 2015). Several research have been done on the use of different waste-based porous materials (WASPORs) as ICWR in concrete. WASPORs were chosen because to their probable appropriateness for this application, as well as their economic and environmental benefits (Al Saffar et al., 2019). Ceramic-recycled aggregate is an example of a WASPOR (Limbachiya et al., 2012) (Etxeberria & Gonzalez-Corominas, 2018). However, due to the narrow pore structure of the attached old mortar, several researchers claimed that recycled concrete aggregate had insufficient desorption characteristics (Kovler & Jensen, 2007). However, several research have suggested that recycled concrete aggregate might be used as ICWRs (Afifi & Abou-Zeid, 2016). According to Lee et al (Lee et al., 2018), when compared to a traditional internal curing agent such as artificial lightweight aggregates and a superabsorbent polymer, recycled aggregates have numerous advantages in terms of availability, waste management and cost. Due to its high water absorption compared to conventional aggregates, the use of recycled aggregates as a source for internal curing would result in the production of a more green sustainable concrete and the reduction of surface cracks, which would increase concrete durability (El-Hawary & Al-Sulily, 2020). The water absorbed by the recycled aggregates during mixing acts as internal curing mechanism, thus reducing or even cancelling the shrinkage due to water evaporation at an early age (Etxeberria & Gonzalez-Corominas, 2018). It was shown by Lee et al. (Lee et al., 2018) that the recycled aggregates can reduce the autogenous shrinkage by nearly one-half of the original Portland Cement concrete.

2.6. Self-compacting concrete with fly ash and recycled aggregates

2.6.1. Fresh properties

Silvestre et al.(2019) explained that with increasing recycled aggregates incorporation levels, both the effective and apparent w/c ratios need be increased to achieve the same goal slump. Water is used more in RFA concrete mixes than in coarse RA concrete mixes. In contrast to recycled aggregates concrete, as the level of fly ash inclusion in concrete rises, a lower w/b ratio is required, since fly ash reduces the amount of water necessary to get the desired slump in RA concrete, it is better to use a high fly ash concentration to achieve the desired slump while avoiding a large increase in the w/b ratio (water content) for a particular RFA incorporation volume ratio and the same fly ash ratio, no increase in water content is required to achieve the same goal slump as the reference concrete, regardless of water absorption. (Silvestre et al., 2019). The slump flow value increased for 50% fly ash but reduced for 75% fly ash in binary mixtures with a w/b ratio of 0.35 and there is a consistent rise in the slump flow diameter with increasing fly ash content for binary SCC mixes with w/b ratios of 0.40 and 0.45, demonstrating that fly ash can improve the filling ability of SCC mixes because finely divided fly ash particles are more spherically shaped than cement. (Guo, Zhang, et al., 2020).

2.6.2. Hardened properties

2.6.2.1.Compressive strength

The compressive strength of RA-SCC was reduced when using 50% and 75% FA. It was discovered that for binary and mixed systems, increasing SCM substitution with OPC is related with a decrease in cube compressive strength, which is mostly attributed to the restricted CaO of FA, resulting in a delayed hydraulic reaction (Guo, Jiang, et al., 2020). Kou and Poon (2013) achieved a long-term investigation on the effect of fly ash on the properties of concrete, it was found that the compressive strength of recycled aggregate concrete was still lower than that of similar natural aggregate concrete after 10 years (Kou & Poon, 2013). SCC mixtures containing 25% FA had 28-day compressive strength intermediate to those containing 50% FA. In general, the use of SCMs has reduced the compressive strength of the mixtures when compared to the usage of 100% cement (Khodair & Bommareddy, 2017). Singh et al. (2016) found that the compressive strength of both low and high volume fly ash-based SCC mixes prepared with RA was found to be lower than the control mixes. The largest drop in compressive strength has been recorded to be between 18 and 19% throughout all curing times (Singh & S P Singh, 2016).

2.6.2.2.Splitting tensile strength:

With increased SCM concentration, the splitting tensile strength of binary mixes decreased. Binary mixes exhibit a 17.2–89% drop in strength when compared SCC conventional concrete (Guo, Jiang, et al., 2020). Kou et al. agreed with the previous statement affirming that the use of fly ash decreases the splitting tensile strength of recycled aggregate concretes (Kou et al., 2011). As for the long-term study of (Kou & Poon, 2013) the splitting tensile strengths of concrete mixes made with 100% recycled aggregate were higher than those of natural aggregate concrete after one year. The concrete mixture including 100% recycled concrete aggregate exhibited the highest splitting tensile strength and strength growth after 5 years (from 16.3%to 45.4%) (Kou et al., 2011).

2.6.2.3.Shrinkage:

The drying shrinkage increased with the larger FA replacement ratio, according to the results. The loss of water in the mixes with large volume FA, notably those with 100% RFA, may have been caused by the slower early hydration rate. As a result, the effective w/b ratio rises, resulting in considerable water loss and further shrinking (Behera et al., 2019). Guo et al. (2020) stated that the drying shrinkage of RA-SCC mixes produced with binary SCMs is smaller than that of high-content PC mixtures. The use of pozzolanic materials decreased the quantity of cement required, resulting in a reduction in the heat of hydration, which is primarily due to the fact that replacing OPC with FA reduced the creep and shrinkage of concrete mixes (Guo, Jiang, et al., 2020). It was found by (Kou et al., 2011) that in recycled aggregate concrete containing fly ash, the drying shrinkage was lower than that of conventional concrete. According to (Khodair & Bommareddy, 2017), when compared to all other mixes, including those with 100% cement, concrete mixtures with 50 percent FA had the lowest total free shrinkage values.

2.6.2.4.Chloride resistance:

If an appropriate amount of FA and low w/c is utilized, the use of fly ash in RCA concrete may considerably improve the resistance to chloride ingress and sulphate erosion, and therefore has the potential to increase the service life of concrete exposed to such a hostile environment. (Limbachiya et al., 2012). Kou et al. (2011) affirmed that the concrete containing recycled aggregate exhibited a more open pore structure than the control concrete, according to the fast chloride ion penetration test. The charge transmitted through the concrete sample was reduced when mineral additive was used (Kou et al., 2011). In the long term research, Kou and Poon (2013) found that after ten years of outdoor exposure, the resistance of recycled aggregate concrete to chloride ion penetration was remained lower than that of regular aggregate concrete. The resistance to chloride ion penetration was considerably enhanced with the addition of fly ash to the concrete mix (Kou & Poon, 2013).

3. Chapter 3: Experimental process

3.1. Materials

3.1.1. Cement

The type of cement used in this study is Portland cement CEM I 52.5R (OPC), with a density of 3.1 kg/dm³ and its composition is described in *Table 2*

3.1.2. Fly ash

The Fly ash utilized during this work was classified as class F, with a density of 2.2 kg/dm³ and its composition listed in *Table 2*

Table 2. Composition of cement and Fly ash (wt%).

	SiO2	CaO	Al2O3	Fe2O3	MgO	SO3	Na2O	K2O	LOI
CEM I 52.5R	19.38	63.53	4.21	3.41	1.41	3.04	0.117	0.53	3.70
FLY ASH	58.4	2.3	21.6	7.3	1.9	0.2	0.9	2.1	3.1

3.1.3. Admixture

The superplasticizer used in this study is MasterEase 3850 which is a reducer additive of high activity water based on the new technology of exclusive PAE polymers for the production of low viscosity concrete even with low water content. It is designed to improve rheology and thus workability of the manufactured concrete. It is dosed 0.5-2.5% by weight of cement, depending on the type of materials.

Table 3. Properties of the superplasticizer used.

Principal function	High activity superplasticizer/ water reducer
Side effect of overdose	Risk of disintegration at high doses
Physical appearance	Yellowish cloudy liquid
Density, 20°C	1.040+0.02 g/cm³
pH, 20°C	6.7±1
Brookfield Viscosity 20°C Sp00/100rpm	< 35 cps.
Chlorides	<0.1%

3.1.4. Aggregates

Natural fines aggregates were replaced with specific percentages of ceramic, concrete, and mixed aggregates in the study. Both the natural and recycled aggregates were obtained locally. Their different physical properties are tabulated below *(Table 4):*

Table 4. Physical properties of the aggregates.

	Raw aggregates			Recycled aggregate 0/4 mm		
	Coarse 4/10 mm	0/2 mm	0/4 mm	Ceramic	Mixed	Concrete
Particle dry density (kg/dm³)	2.64	2.58	2.59	2.11	2.26	2.13
Absorption (%)	0.75	1.7	1.79	12	7.21	10,4
30min absorption (%)	0.15	1.25	1.253	12	7.21	10,4

(a) (b) (c)

Figure 1. Recycled fine aggregates (a) Ceramic, (b) Concrete and (c) Mixed.

The aggregate particle sizes utilized were in line with the UNE EN 933-1:1998 standard. The sieve's configuration was employed such that it rattles every 10 seconds for a total of 2 minutes. Following this, the next step was to weigh the material retained on each sieve so that the data for the grading distribution curve of both natural and recycled aggregates could be drawn *(figure 2).* The fine aggregates were (0-4 mm) and (0-2mm), whereas for coarse aggregates (4-10 mm), the graphs below show the grading distribution of the aggregates used.

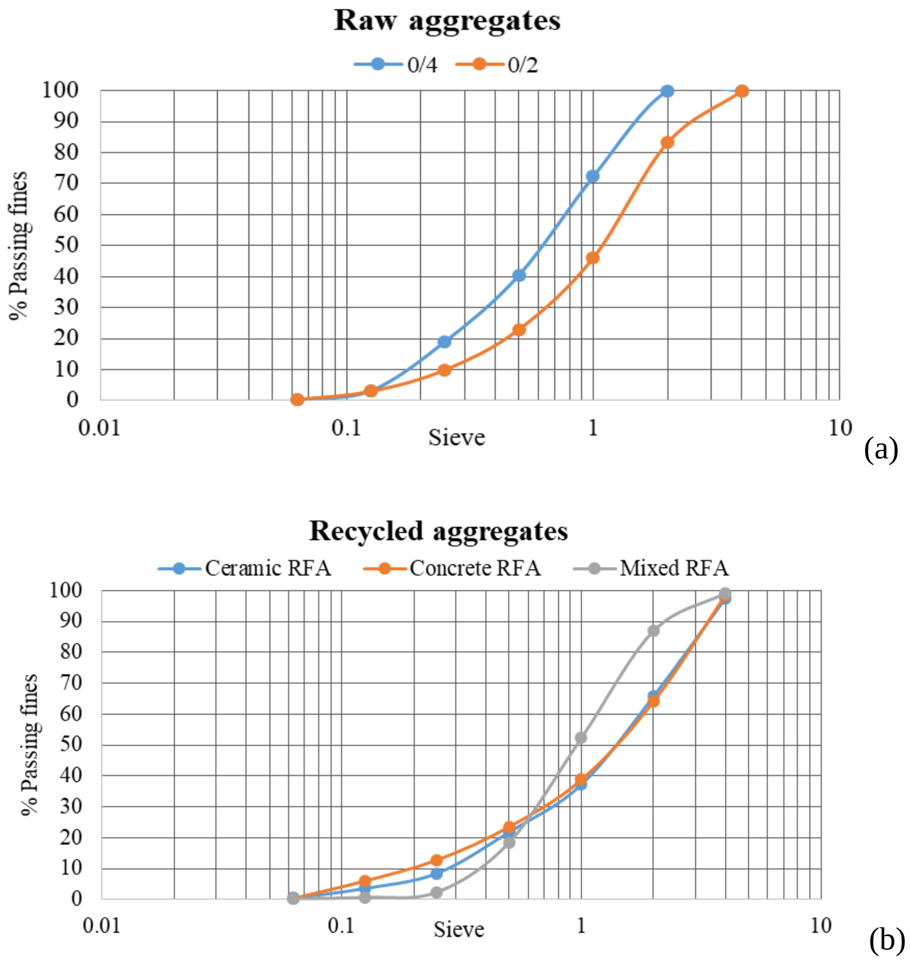


Figure 2. Grading distribution (a) raw aggregates (b) recycled aggregates.

3.2. Mix proportions-Validation by fresh properties

3.2.1. Mix proportions

In this study, all concrete mixtures were prepared and produced in the Laboratory of Technology of Structures and Materials "Lluis Agulló"of the UPC. The concrete mixture should meet the requirements of SCC and high-performance concrete as in, to have three key properties filling ability, passing ability and segregation resistance as well as having a strength higher than 50 MPa, defined in EFNARC guideline (see Chapter 2). The different characteristics of the concrete mixtures are:

- The effective water-to-cement ratio was fixed to 0.32 for all the mixtures.
- Natural Fine Aggregate (0/4mm) were replaced with 60% Recycled Fine Aggregates.
- Fly Ash replacement was 30% and 50% of cement weight.

- The recycled aggregates were used in dry condition with taking into account the amount of absorbed water in the mix proportions

Table 5, 6 and 7 describe the mix proportions of concretes produced with 100% OPC, 70%OPC with 30% of FA and 50%OPC with 50% FA, respectively. The values of each of the material employed are expressed in Kg for production of 1 m^3 of concrete. The amount of superplasticizer (SP) is described in percentage with respect to cement weight.

Table 5. Mix proportions of the concretes with 100% Portland cement.

			Raw aggregate			RFA	Total water	Effect w/c	SP (%)	Fresh state properties		
	cement	Fly ash	4/10 coarse	0/4	0/2	0/4				Slump Flow (mm)	V-Funnel (sec)	L-Box
Control	500	-	834.2	620.6	266	-	175	0.32	2	750	11.28	0.83
Cer-RFA60	500	-	834.2	248.3	266	303.4	206.7	0.32	2.16	720	14	0.85
Con-RFA60	500	-	834.2	248.3	266	306.2	202.2	0.32	2.12	800	10	0.89
Mixed-RFA60	500	-	834.2	248.3	266	324.9	193.8	0.32	2.24	700	11.33	0.81
EFNARC Guidelines										650-800	6-12	0.8-1.0

Table 6. Mix proportions of the concretes with 30% Fly Ash replacement.

			Raw aggregate			RFA	Total water	Eff w/c	SP (%)	Fresh state properties		
	cement	Fly ash	4/10 coarse	0/4	0/2	0/4				Slump Flow (mm)	V-Funnel (sec)	L-Box
FA30-Control	350	150	814.6	606	259.7	-	175	0.32	1.64	690	8.5	0.87
FA30-Ceramic-RFA60	350	150	814.6	242.4	259.7	296.2	205.9	0.32	1.75	710	11.76	0.88
FA30-Concrete-RFA60	350	150	814.6	242.4	259.7	299	201.5	0.32	1.76	710	11	1
FA30-Mixed-RFA60	350	150	814.6	242.4	259.7	317.3	193.3	0.32	1.76	690	9.0	0.83
EFNARC Guidelines										650-800	6-12	0.8-1.0

Table 7. Mix proportions of the concretes with 50% Fly Ash replacement.

			Raw aggregate			RFA	Total water	Eff w/c	SP (%)	Fresh state properties		
	cement	Fly ash	4/10 coarse	0/4	0/2	0/4				Slump Flow (mm)	V-Funnel (sec)	L-Box
FA50-Control	250	250	801.5	596.3	255.6	-	175	0.32	1.64	780	7.8	0.9
FA50-Ceramic-RFA60	250	250	801.5	238.5	255.6	291.5	206.5	0.32	1.78	780	11.49	0.88
FA50-Concrete-RFA60	250	250	801.5	238.5	255.6	294.2	201.1	0.32	2.24	730	11.78	0.9
FA50-Mixed-RFA60	250	250	801.5	238.5	255.6	312.2	193	0.32	2.24	780	8.0	1
EFNARC Guidelines										650-800	6-12	0.8-1.0

3.2.2. Fresh properties tests

In order to evaluate the workability of the concretes, as mentioned in the chapter before, the filling ability, passing ability and segregation resistance must be tested, through the Slump Flow test, the L-Box test method and the V-Funnel test, respectively, following the EFNARC Guidelines (EFNARC, 2002).

Slump Flow test

After mixing the concrete, the fresh mix is poured in the slump cone that is placed in the center of the moisten base plate. It is filled in one continuous layer without rodding or vibrating or any manual agitation, only the surplus is removed from the top of the cone with the trowel. The cone is raised vertically and allows the concrete to flow out freely *(figure 3)*. The slump flow is measured by rounding the mean base diameter of the concrete sample to the nearest 10 mm at the end of the slump test. Because of the viscous nature of SCC, the slump flow measurement readings were taken when there was no observable movement of the concrete, about 60 seconds after the slump cone was removed. The result indicates the filling ability of SCC. According to EFNARC guidelines (EFNARC, 2002), the higher the slump flow value, and the greater its ability to fill formwork under its own weight. A value of at least 650mm is required for SCC. There is no generally accepted advice on what are reasonable tolerances about a specified value, though ± 50mm, as with the related flowtable test, might be appropriate.

Figure 3. Slump flow test.

L-Box test method

The L-Box test *(figure 4)* assesses the flow of the concrete and the extent to which it is subjected to blocking by reinforcement. The equipment consists of a rectangular-section box in the shape of an ‘L’ with a vertical and horizontal sections divided by a moveable gate, in front of which vertical lengths of reinforcement bar are inserted. After filling the vertical part with concrete, the gate is raised to let the concrete to flow into the horizontal part. When the flow stops, the height of the concrete at the end of the horizontal section is given as a percentage of the vertical section (H2/H1), namely, the blocking ratio. When the concrete is at rest, it shows the slope of the surface. This a measure of concrete passing ability, or how difficult it is for concrete to pass through the bars. If the SCC has perfect fresh properties, the blocking ration is equal to 1 and in contrast, it is equal to zero if it is too stiff or segregated. The EU research team (EFNARC & The European Project Group, 2005) suggested a minimum acceptable value of 0.8. Besides, at 200mm and 400mm from the gate, the horizontal part of the box can be marked and the times taken to reach these points measured. These are referred to as the T20 and T40 timings, and they indicated the filling capacity. T20 and T40 times can give some indication of ease of flow, but no suitable values have been generally agreed (EFNARC, 2002).

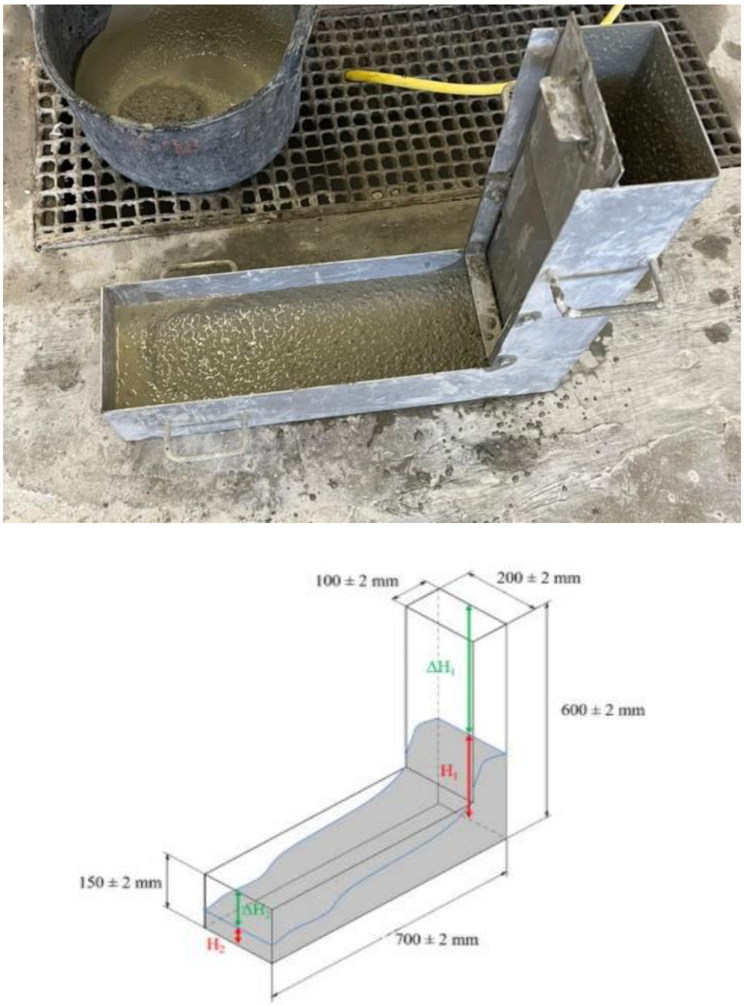


Figure 4. L-box test equipment and its measurements.

V-Funnel test

The V-Funnel test *(figure 5)* is used to measure the concrete's filling ability (flowability). Concrete is poured into the funnel and the time it takes for it to flow through the apparatus is recorded. The funnel can be then refilled with concrete and put aside for 5 minutes to settle. If the concrete segregates, the flow time will dramatically increase. According to EFNARC, a flow period of 10 seconds is deemed adequate for SCC. The inverted cone shape restricts flow, and prolonged flow durations could increase the mix's susceptibility to blocking. Concrete segregation will indicate a less continuous flow with an increase in flow time after 5 minutes of settling (EFNARC, 2002).

Figure 5. V-Funnel test equipment.

3.2.3. Validation of the fresh properties

Slump test, V-Funnel test and L-Box test were the tests done on the fresh concrete in order to evaluate the filling ability, the passing ability and the segregation resistance of the different concrete mixtures. The mix proportions (*Tables 5,6 and 7*)(see above) demonstrate the results obtained from these tests for each mixes with 100% Portland cement and with 30% and 50% replacement of Fly Ash.

From the results on the tables above, it can be concluded that all the mixes satisfy the SCC requirements according to the EFNARC guidelines as in the slump test being between 650-800 mm, V-Funnel test between 6-12 sec and the ratio of the difference in height of the L-Box between 0.8-1.0. While analyzing the mixes without recycled aggregates, it can be seen that the FA50-Control Mix and Control Mix showed more workability compared with FA30-Control. Also, when adding 50% of fly ash in the mixes the filling ability increases compared with 100% Portland cement concretes, however it decreased when using 30% fly ash. And in the mixes with recycled aggregates it can be noticed that the V-Funnel results showed a less continuous flow than control mixes. The L-Box test showed that recycled aggregate concretes have better passing ability compared with control mixes except for recycled mixed aggregates when using 30% fly ash replacement and 100% PC, while recycled concrete aggregates concretes have the highest blocking ratio meaning it has the highest ability to flow through tight openings.

It can be concluded that that as there is an increase in Fly Ash replacement, the workability also increases and this is due to the reduction of aggregate in the mixes. Also, the superplasticizer demand decreases when using FA. Similar conclusion was obtained by Falmata et al. stating that the addition of FA reduces the dosage of superplasticizer and improves the passing ability (Falmata et al., 2020). Also, when incorporating recycled aggregates there is a less continuous flow, Behera et al. obtained the same result explaining that it's due to the fact that recycled aggregates absorb more water, making the RFA particles heavier to fall, thus passing through the V-Funnel takes more time (Behera et al., 2019)

3.3. Concrete production and test procedure

Before starting to determine the hardened properties, the concrete mix proportions had to be validated according to fresh state requirements for SCC. After the fresh properties were validated, to determine the hardened properties, all the moulds were prepared by putting some oil on them in order to ease the demoulding procedure. Afterwards, the constituents of concrete should be weighed. Then, the mixing process can start by wetting the mixer with water then the coarse aggregate were put first, followed by the fine aggregate in the mixer and the absorbed water was added. The combination of fly ash and cement was added with the amount of effective water. Later, a superplasticizer was gradually added until the paste was homogenous and workable. The entire amount of superplasticizer applied was previously specified in all situations. The concrete is filled into the moulds, no vibration is needed in this case, and the specimens are covered with a damp cloth to avoid evaporation of the water. After 24 hours, the specimens are demoulded and put in the climatic chamber. The curing times vary depending on the age of the specimen and the need to test the concrete's performance.

Figure 6. The weighed materials and the mixer used.

As it is mentioned above, the fresh properties of concretes could be validated according to EFNARC guidelines. Consequently, the hardened properties of all the mixtures were evaluated.

3.3.1. Physical properties

The tests were performed in accordance with the standard UNE-EN 12390-7:2020 “Testing hardened concrete - Part 7: Density of hardened concrete”. To determine the physical properties of the concretes, the density, the water absorption and the porosity were calculated after 28 and 56 days of curing using the following formulas:

$$Dry\ Density = \frac{Dry\ weight}{Saturated\ weight - Hydrostatic\ weight}$$

$$SSD\ Density = \frac{Saturated\ weight}{Saturated\ weight - Hydrostatic\ weight}$$

$$Apparent\ Density = \frac{Dry\ weight}{Dry\ weight - Hydrostatic\ weight}$$

$$Absorption = \frac{Saturated\ weight - Dry\ weight}{Dry\ weight} * 100$$

$$Porosity = \frac{Apparent\ density - Dry\ density}{Dry\ density} * 100$$

The test started after 28 days of curing, three cube specimens of 100x100x100 mm were used. The weight after taking out the specimens of the chamber was taken that is called the saturated weight, then the specimen was directly submerged in water and the weight was saved (hydrostatic weight). Afterwards, the specimens were put in the oven at 100°C for 24 hours. Then the dry weight was noted after the completion of these 24 hours. The average value of the 3 specimens was taken in order to calculate the physical properties of the concretes.

3.3.2. Compressive strength

The compressive strength was tested following the standard UNE-EN12390-3:2020 “Testing hardened concrete - Part 3: Compressive strength of test specimens”. A machine with a loading capacity of 3000 kN was used *(figure 7).* Three cubic specimens of 100mm were tested at the ages of 7,28 and 56 days. The process entailed continually applying a load to the specimen at a rate of around 0.5 MPa/s. The maximum load value is determined when the specimens deforms immediately before a physical break occurs.

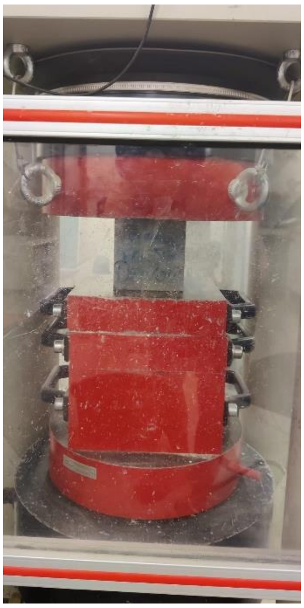


Figure 7. Compression strength test.

3.3.3. Splitting tensile strength

The splitting tensile strength test was carried out in compliance with the standard UNE-EN 12390-6:2010 "Testing hardened concrete - Part 6: Tensile splitting strength of test specimens" Two cylindrical specimens of 200 x ϕ100 mm were tested for each type of concrete at 28 days. Tensile stresses were created by placing the specimen horizontally and applying a vertical load on the cylinder. The load is typically applied continuously and gradually, though at a slow speed of 0.03 MPa/s.

3.3.4. Modulus of elasticity

The precise value of concrete's modulus of elasticity can be established by performing a compression test on a cylindrical concrete specimen in the laboratory following the standard UNE-EN 12390-13:2014 "Testing hardened concrete - Part 13: Determination of secant modulus of elasticity in compression". During the test, the deformation of the specimen is examined in relation to various load variations. These observations result in a Stress-Strain graph (load-deflection graph) that is used to calculate the modulus of elasticity of concrete. The modulus is defined by the slope of a line formed in the stess-strain curve from a stress value of zero to a compressive stress of 0.45f'c (working stress).

3.3.5. Shrinkage

a) Autogenous shrinkage

In this study, autogenous shrinkage test *(figure 8)* following the recommendations of the Japan Concrete Institute (JCI) was conducted in all concrete mixtures for 7 days after concrete mixing. Strain gauges were vertically embedded in the concrete specimens using cylindrical moulds of 300mm and 150mm diameter. To minimize moisture loss from the concrete specimen, the free upper surfaces were immediately covered with layers of aluminum foil after casting. Approximately 10 minutes after casting, the specimens were sealed and connected to the data acquisition system. The specimens were kept in the climatic chamber at a temperature of 25 ± 2 °C and 50 ± 5% of humidity throughout the whole test period. After 7 days, the results were obtained by the average of testing two specimens.

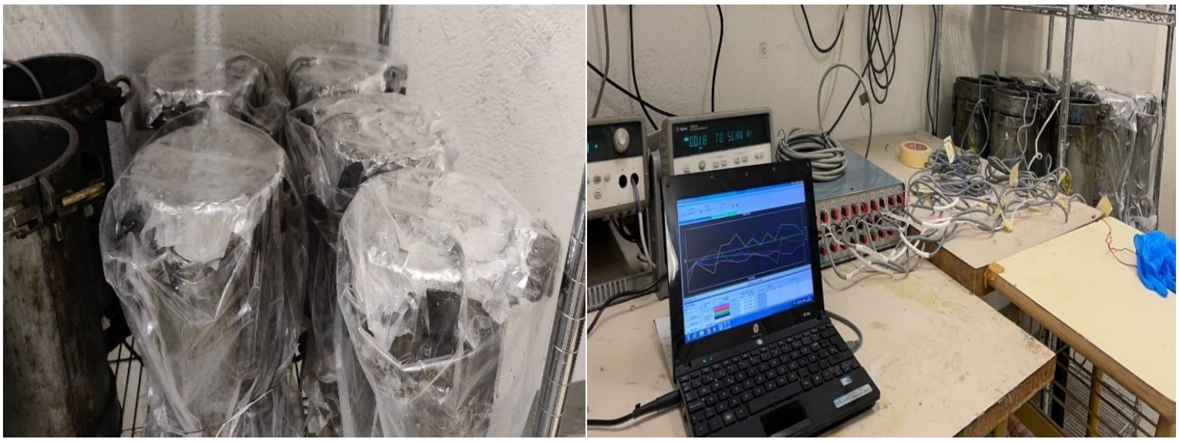


Figure 8. Autogenous shrinkage test.

b) Drying shrinkage

Drying shrinkage was measured using the procedure in ASTM C596 (2009). In order to determine the drying shrinkage in this study, 70 x 70 x 285 mm prismatic specimens with a stainless steel studs at both ends were used. The specimens were demoulded and immersed in water for three days. The first length measurement and initial mass were obtained immediately after taking the specimens out of water and wiped with a damp cloth, they were measured using a length comparator and a scale, and then they were placed in the climatic chamber at a temperature of 25 ± 2 °C and 50 ± 5% of humidity. The specimens length change and mass were measured every day for 28 days and then for 56th day. Each result was an average of two specimens per concrete mixture.

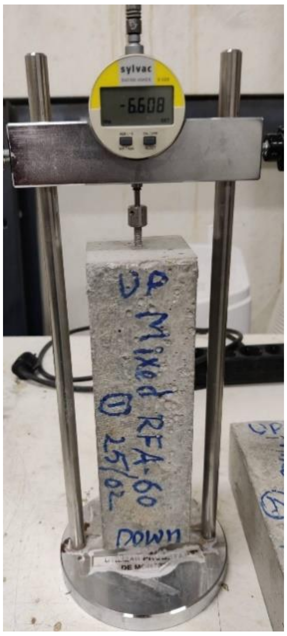


Figure 9. Drying shrinkage test.

3.3.6. Chloride penetration test

Rapid chloride penetration testing was used to evaluate the resistance of concrete disc specimens of 100mm diameter and 50mm thickness to chloride ingress at 28 days and 56 days. A 60 V dc is maintained between the ends of the specimen, one of which is immersed in sodium chloride and the other in sodium hydroxide. The total charged passed 'Q' is calculated according to the standard ASTM_C1202 using the following formula, where $I_0 \, and \, I_f$ are the current amperes immediately after the voltage is applied and the current amperes at t min after voltage is applied, respectively.

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

The total charge passed, measured in coulombs, has been linked to the specimen's resistance to chloride penetration. Below, the table showing the chloride ion penetrability based on charge passed:

Table 8. 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

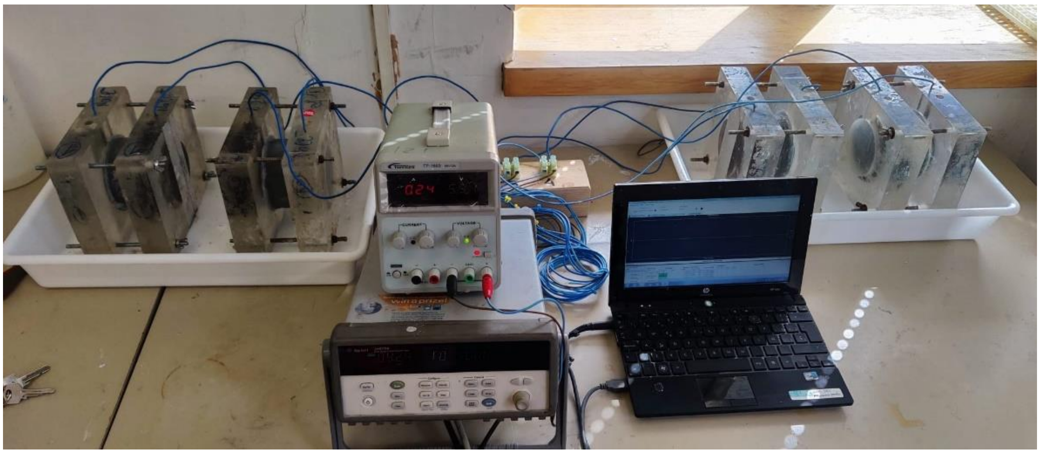


Figure 10. Chloride penetration test.

4. Chapter 4: Results and analysis

4.1. Physical properties

The physical properties of the concrete mixes were tested after 28 and 56 days of curing. The results of the density, water absorption and porosity are presented on the tables below.

Table 9. Physical properties of concretes with 100% Portland cement.

	Dry Density (g/cm³)		SSD Density (g/cm³)		Aparent Density(g/cm³)		Absorption (%)		Porosity (%)	
	28d	56d	28d	56d	28d	56d	28d	56d	28d	56d
Control Mix	2.35	2.38	2.42	2.44	2.51	2.52	2.64	2.34	6.63	5.90
Ceramic RFA 60	2.29	2.30	2.37	2.37	2.49	2.48	3.26	3.02	8.11	7.46
ConcreteRFA 60	2.33	2.34	2.42	2.41	2.55	2.53	3.65	3.27	9.32	8.28
Mixed RFA 60	2.28	2.29	2.36	2.36	2.48	2.47	3.48	3.16	8.65	7.81

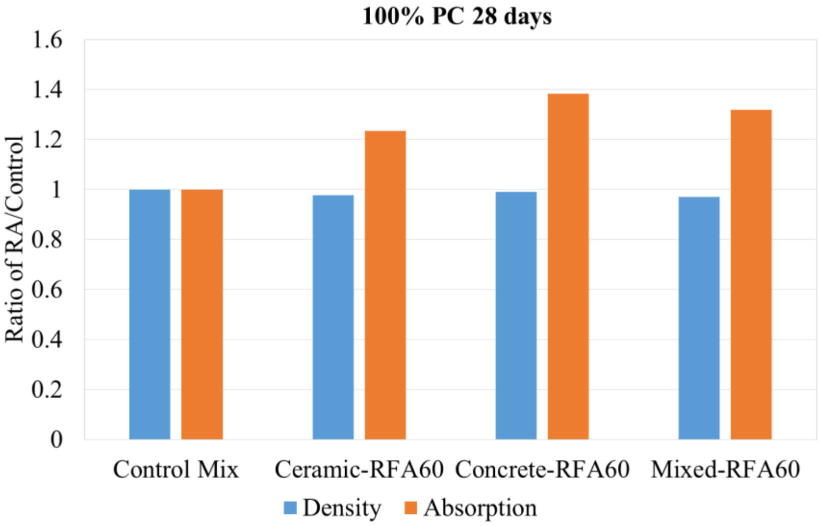
Table 10. Physical properties of concretes with 30% Fly ash replacement.

	Dry Density (g/cm³)		SSD Density (g/cm³)		Aparent Density(g/cm³)		Absorption (%)		Porosity (%)	
	28d	56d	28d	56d	28d	56d	28d	56d	28d	56d
FA30-Control Mix	2.30	2.38	2.41	2.44	2.57	2.54	4.49	2.67	11.55	6.80
FA30-CeramicRFA60	2.27	2.31	2.38	2.47	2.55	2.58	4.93	2.90	12.58	7.47
FA30ConcreteRFA60	2.29	2.34	2.37	2.41	2.51	2.52	3.85	3.05	9.64	7.68
FA30-Mixed RFA 60	2.23	2.25	2.32	2.33	2.44	2.45	3.97	3.63	9.70	8.89

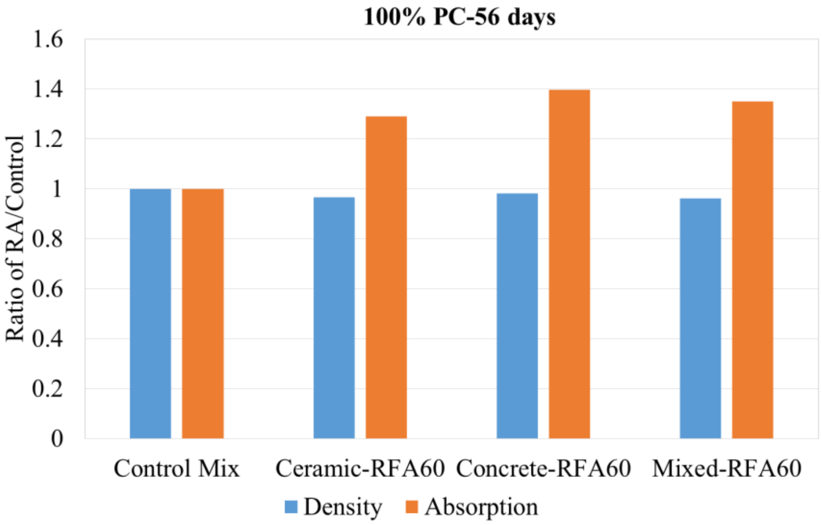
Table 11. Physical properties of concretes with 50% Fly ash replacement.

	Dry Density (g/cm³)		SSD Density (g/cm³)		Aparent Density(g/cm³)		Absorption (%)		Porosity (%)	
	28d	56d	28d	56d	28d	56d	28d	56d	28d	56d
FA50-Control Mix	2.27	2.29	2.35	2.35	2.45	2.44	3.18	2.76	7.80	6.73
FA50-CeramicRFA60	2.26	2.26	2.34	2.33	2.45	2.43	3.51	3.13	8.61	7.61
FA50ConcreteRFA60	2.21	2.27	2.36	2.36	2.61	2.48	6.80	3.81	17.7	9.46
FA50-Mixed RFA 60	2.20	2.26	2.33	2.33	2.54	2.44	6.14	3.30	15.6	8.03

Comparative graphs were made in order to check the density and water absorption of the concretes with recycled aggregates in comparison with the control mixes as well as when using fly ash replacement. The graphs are illustrated below *(figures 11, 12, 13).*



(a)



(b)

Figure 11. Comparison of density and absorption between control mix and RFA mixes at (a) 28 days and (b) 56 days age of 100% PC concretes.

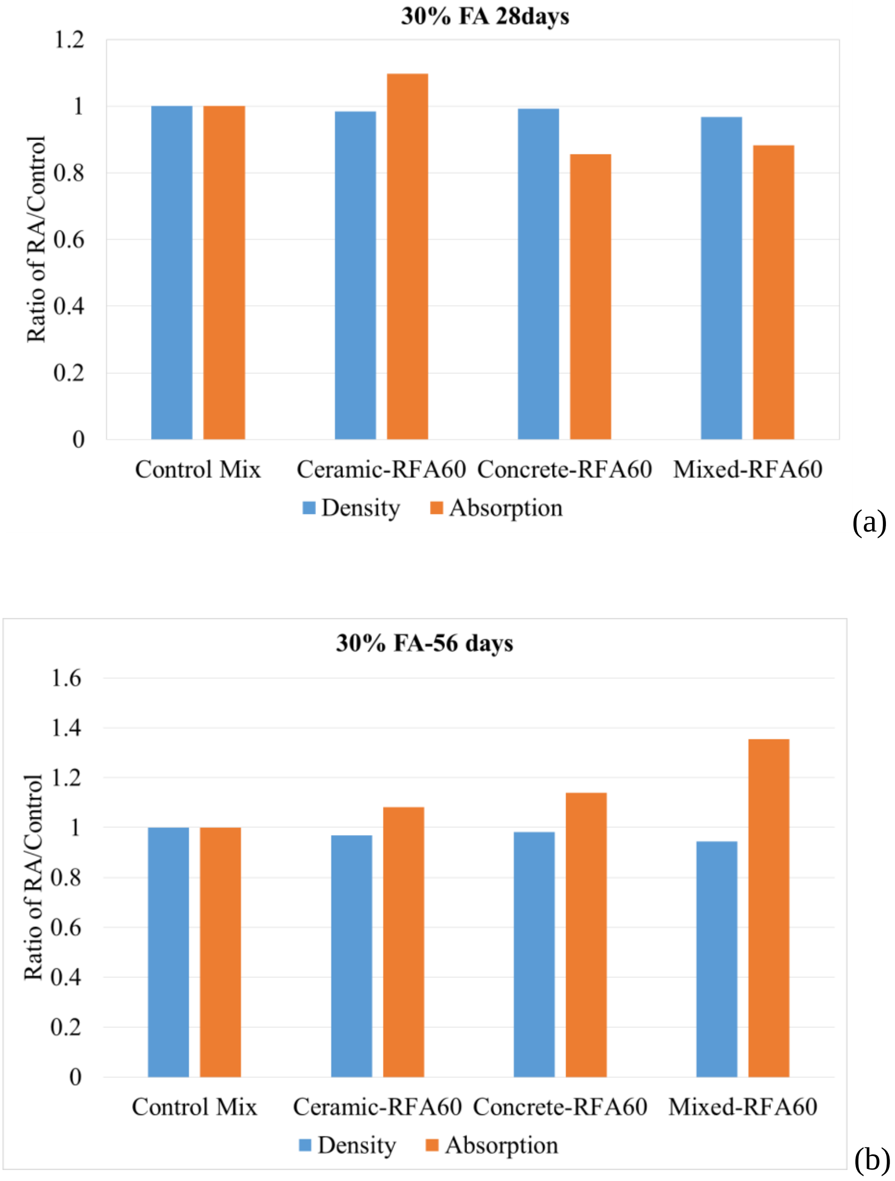


Figure 12. Comparison of density and absorption between control mix and RFA mixes at (a) 28 days and (b) 56 days age of 30% fly ash replacement.

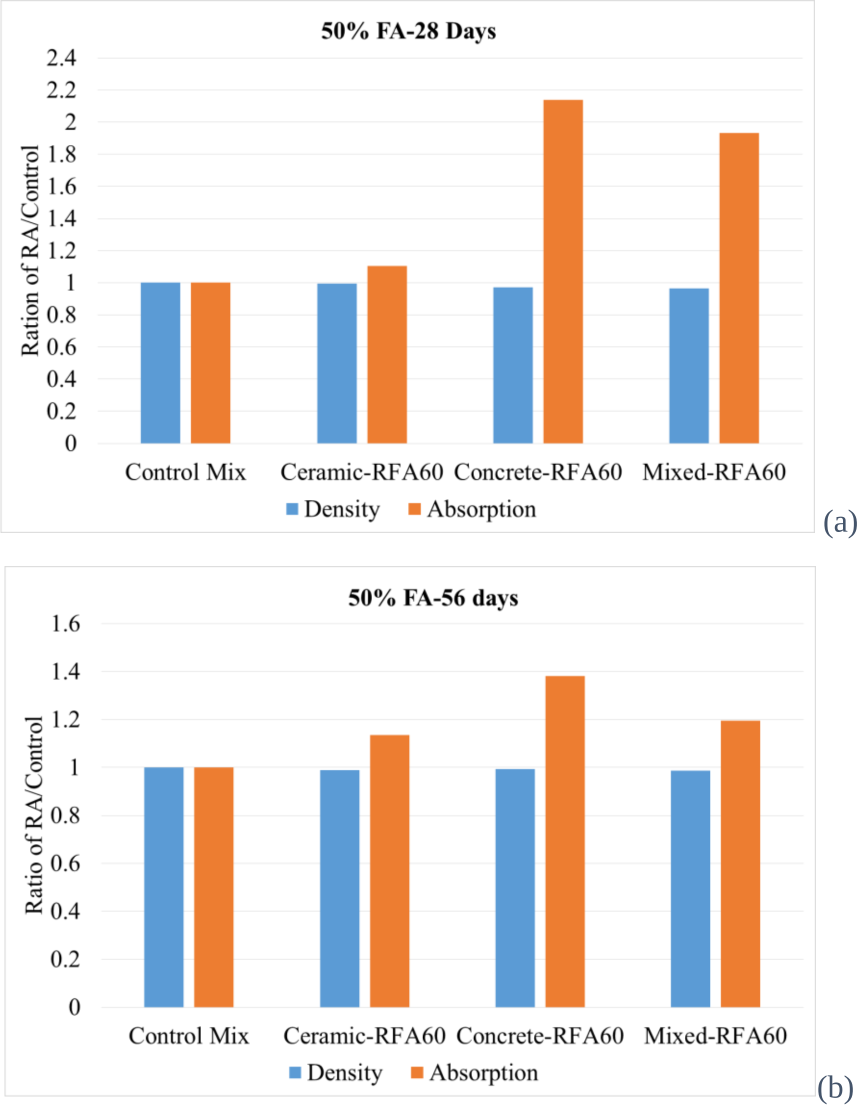


Figure 13. Comparison of density and absorption between control mix and RA mixes at 28 days age of 50% fly ash replacement.

From the graph of the mixes with 100% PC (*Figure 11*), it can be seen that the mixes with recycled aggregates showed higher water absorption compared with the control mix and the mix with recycled concrete aggregates had the highest water absorption capacity 38% more than control mix. In addition, the dry density was almost equal for all the mixes with only Portland cement. The same behavior remains similar after 56 days of curing.

While having 30% replacement of fly ash, the density remains almost the same for all the mixes at 28 days. However, the water absorption is highest than control mix when using recycled ceramic aggregates and lowest for the other two types of recycled aggregates. Yet, at 56 days the RAC have higher water absorption than control mix and the highest is observed in FA30-Mixed RFA60 by 35% and the dry density remains the same as for 28 days.

For the mixes of 50% fly ash, the dry density is also similar for all the concretes at 28 and 56 days. But the water absorption of the concretes with recycled aggregates is higher. However, the water absorption FA50-Concrete RFA-60 and FA50-Mixed RFA-60 is significantly higher this due to the use of high amount of superplasticizer during mixing.

Also, for the three cases (100%PC, 30% FA and 50%FA), it can be concluded that when there is the incorporation of recycled aggregates in the mix, the water absorption increases and the dry density remains similar as the control mix. It is observed that at 56 days the water absorption capacity decreases in comparison with 28 days but still it is higher in recycled aggregates concretes than control mixes. This lower absorption after more curing time indicates that the concrete self-weight has attained good compaction, because of the enhanced workability, compaction is expected to be improved, especially in the presence of FA (Khatib, 2008). Similarly, (Etxeberria, 2014) found that water absorption increased by 40% in comparison with conventional concrete.

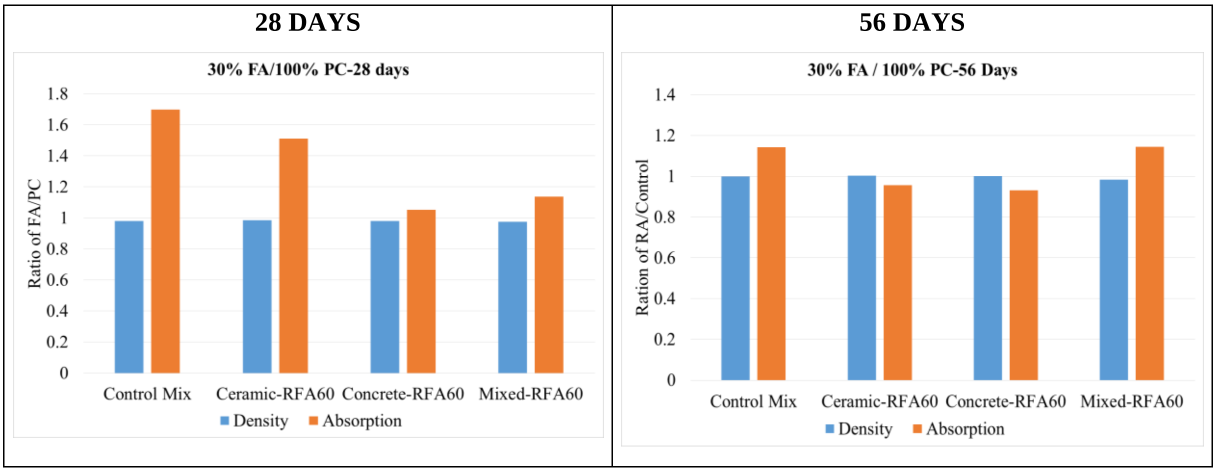


Figure 14. Comparison of density and absorption between 100% PC and 30% FA concretes at 28 and 56 days

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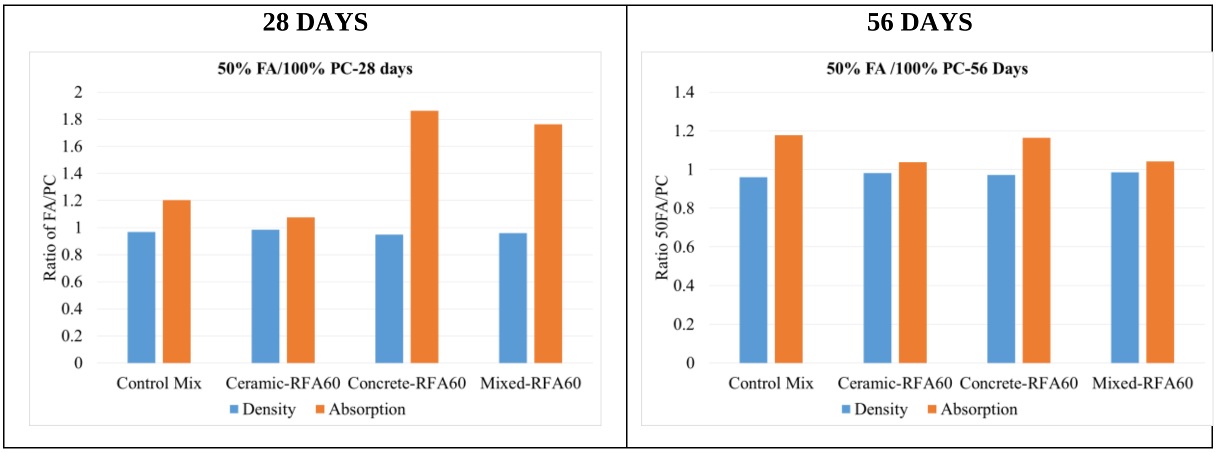


Figure 15. Comparison of density and absorption between 100% PC and 50% FA concretes at 28 and 56 days.

Deriving out of the graphs and the results above for 30% fly ash replacement it is noticeable that the ratio is high so the water absorption is higher when compared with 100% PC, but the concretes with recycled aggregates have lower water absorption compared with FA30-Control mix. However it decreases for 56 days but still control mix having the higher rate followed by Mixed RAC. It can be deduced that when incorporating 30% FA in the mixes, water absorption increases more especially in control mix. Concerning 50% FA, no major difference was observed in density at both 28 and 56 days, however due to SP as explained before, the water absorption is higher than 100% PC but at 56 days there is no high difference between the different concretes however the control mix has a slight higher water absorption compared with the others. So, when there in an increase in fly ash content, the water absorption also increases in comparison with 100% PC mixes. According to Singh et al. (2019) an increase in water absorption with an increase in FA indicates a rise in accessible pore volume; water absorption tests generally reveal a direct proportionate relationship with the amount of FA, meaning it increases when the content increases and vice versa (Singh et al., 2019).

4.2. Hardened properties

4.2.1. Compression test

The compressive strength results at the age of 7, 28 and 56 days of the different concretes with 100% Portland cement, 30% and 50% fly ash are tabulated below in *Table 11*, *Table 12* and *Table 13*, respectively.

Table 12. Compressive strength of the concretes with 100% Portland cement.

	Compressive Strength (MPa)		
	7 days	**28 days**	**56 days**
Control Mix	71.35	84.77	87.27
Ceramic RFA-60	80.44	87.51	87.44
Concrete RFA-60	72.29	78.88	78.85
Mixed RFA-60	69.80	77.29	79.81

Table 13. Compressive strength of the concretes with 30% Fly Ash replacement.

	Compressive Strength (MPa)		
	7 days	**28 days**	**56 days**
FA30-Control Mix	64.82	76.76	81.46
FA30- Ceramic RFA-60	60.39	74.17	80.02
FA30-Concrete RFA-60	52.49	68.08	76.89
FA30-Mixed RFA-60	47.83	61.49	72.29

Table 14. Compressive strength of the concretes with 50% Fly Ash replacement.

	Compressive Strength (MPa)		
	7 days	**28 days**	**56 days**
FA50-Control Mix	41.87	59.79	72.93
FA50-Ceramic RFA-60	46.54	61.96	75.50
FA50-Concrete RFA-60	41.36	56.06	66.72
FA50-Mixed RFA-60	43.03	52.49	56.78

It is easily noticeable that as the curing age increases, the compressive strength increases too and for all the cases with 100% Portland cement, 30% and 50% fly ash replacement. However, as there is an increase of fly replacement, the compressive strength tends to decrease in comparison with 100% Portland cement mixes. The graphs below illustrate the ratio of the use of recycled aggregates in comparison with control mix for each case.

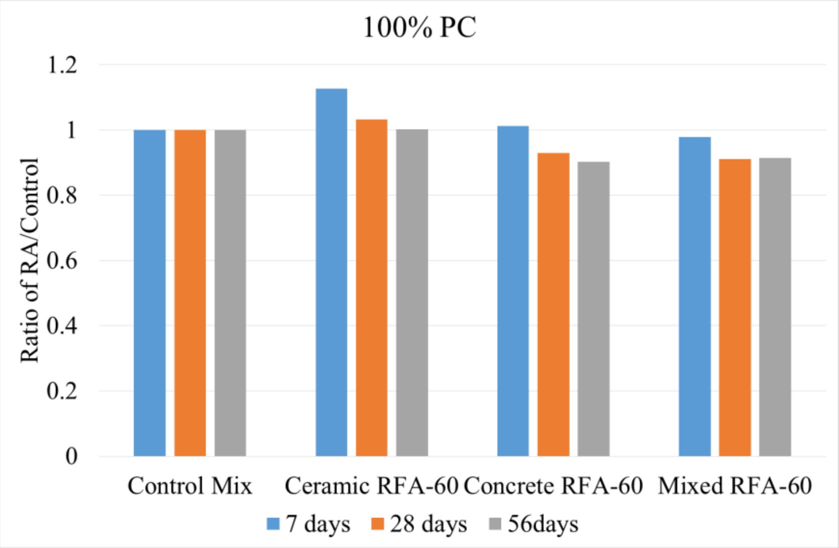


Figure 16. Comparison of compressive strength of Control mix and RA mixes with 100% Portland cement.

The Ceramic RFA-60 mix showed the highest compressive strength at 7 days compared with all the other concretes including control mix and the two other RFA concretes have almost similar values with Control mix at the same curing age. At 28 days, the difference is minimal between Ceramic RFA-60 and Control Mix but for Concrete RFA-60 and Mixed RFA-60 it is less than the two others. And at 56 days, the behavior remains the same as 28 days.

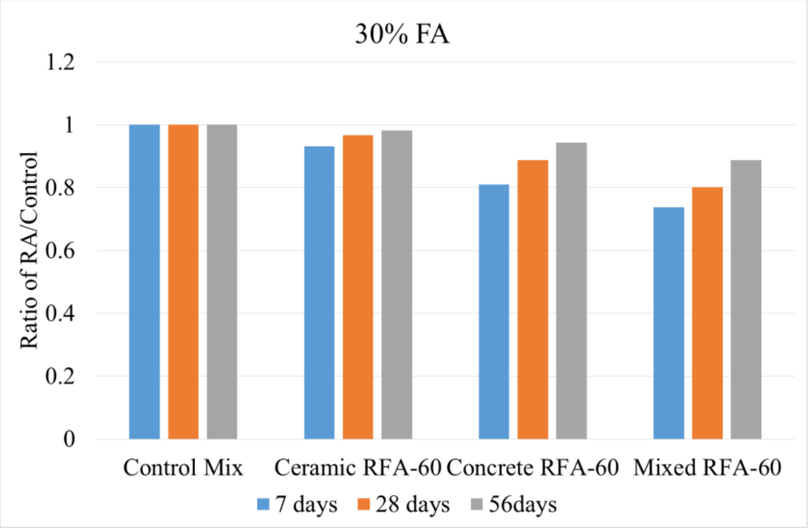


Figure 17. Comparison of compressive strength of Control mix and RA mixes with 30% fly ash replacement.

While using 30% fly ash replacement, the behavior of the concretes is similar, the recycled aggregates mixes have lower compressive strength than FA30-Control mix at 7, 28 and 56 days and when comparing the types of recycled aggregates, the mix with recycled ceramic aggregates has higher compressive strength than concrete and mixed recycled aggregates.

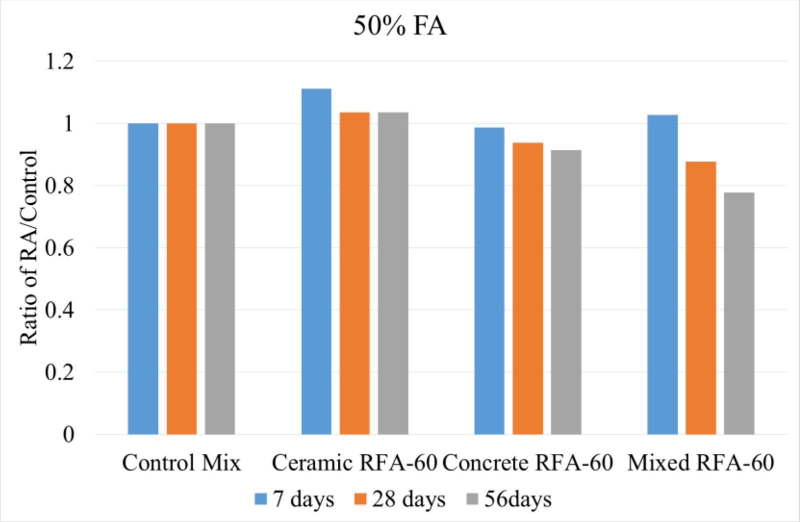


Figure 18. Comparison of compressive strength of Control mix and RA mixes with 50% fly ash replacement.

The mixed recycled aggregates concrete with 50% fly ash showed the lowest compressive strength at 28 and 56 days compared with the other concretes. On the other hand, the FA50-Ceramic RFA-60 has the highest compressive strength with the highest difference at 7 days. As the curing age increases, the concretes with mixed and concrete recycled aggregates showed lowest compressive strength in comparison with conventional concrete.

Overall, it may be said that the mix with Ceramic RFA-60 showed the highest compressive strength in 100% Portland cement and 50% fly ash. The authors Torkittikul and Chaipanich got the same results that the compressive strength of ceramic concrete increased by 7.5% after 28 days when ceramic aggregates were used at 50% by weight, compared to the control concrete (Torkittikul & Chaipanich, 2010). The same authors agree with (Etxeberria, 2014) that stated this increase in strength is most likely owing to the rough ceramic's improved interfacial zone, as well as the strength of the sintered ceramic (mullite). In addition, from the results it can also be concluded that the control mixes have highest compressive strength than the mixes with recycled concrete and mixed aggregates, according to Khodair and Bommareddy (Khodair & Bommareddy, 2017), the weak bond between the mortar and aggregate in recycled concrete aggregates (RCA), as well as the inferior quality of RCA compared to natural aggregates can explain this decrease in strength. RCA is made out of natural aggregate with old cement paste attached, its presence depletes a portion of the design mix water required for the hydration process, lowering the mix's compressive strength. Also, Aslani et al.(2018) obtained the same conclusion explaining that because of the poor quality of the RA that was crushed, the concrete has weaker interfacial transition zones (ITZ), resulting in a lower compressive strength than the parent concrete (Aslani et al., 2018)

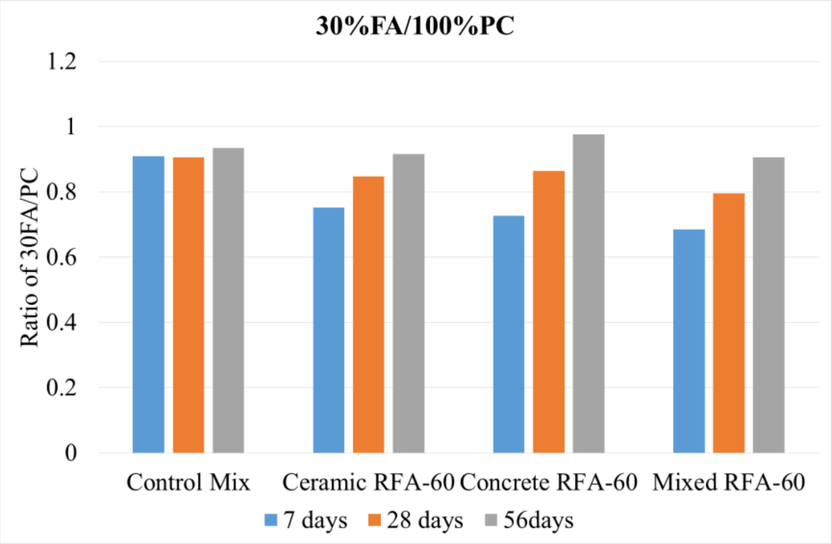


Figure 19. Comparison of compressive strength between 100% PC and 30% FA concretes.

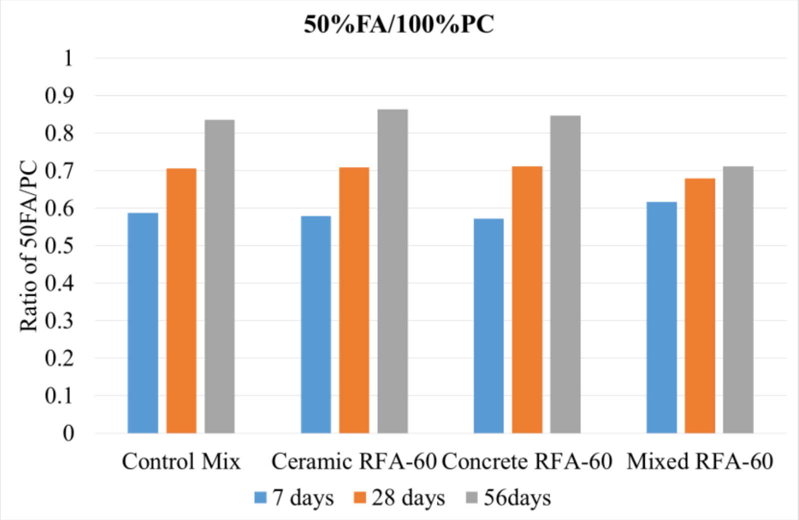


Figure 20. Comparison of compressive strength between 100% PC and 50% FA concretes

For 30% FA replacement, the compressive strength of recycled aggregate concretes decreased by 18% and 7% at 7 days and 28 days, respectively in comparison with conventional concrete and the same ratio was observed at 56 days. In mixes with 50% fly ash replacement, the behavior of the concrete is similar with a low ratio at 7 days and it increases with the increase in curing time meaning lower compressive strength for FA50 mixes compared with 100% PC mixes.

So as the content of fly ash increases, the highest is the difference with 100% PC mixes meaning the lowest the compression strength. Similar results were obtained by (Guo, Jiang, et al., 2020) when 50% and 75% of FA was used, the compressive strength of RA-SCC was decreased due to the limited CaO of FA, resulting in a delayed hydraulic reaction. Also, Higher replacement levels of fly ash led to a reduction in the compressive strength (Celik et al., 2014) (P. R. Da Silva & De Brito, 2015).

4.2.2. Splitting tensile strength

The table below illustrates the splitting tensile strength of the 100% Portland cement mixes after 28 days of curing. Also, the graph represents the comparison of the control mix with the concretes having recycled aggregates.

Table 15. Splitting tensile strength of the 100% Portland cement mixes.

	Tensile (MPa)
Control Mix	3.73
Ceramic RFA-60	3.76
Concrete RFA-60	3.65
Mixed RFA-60	3.84

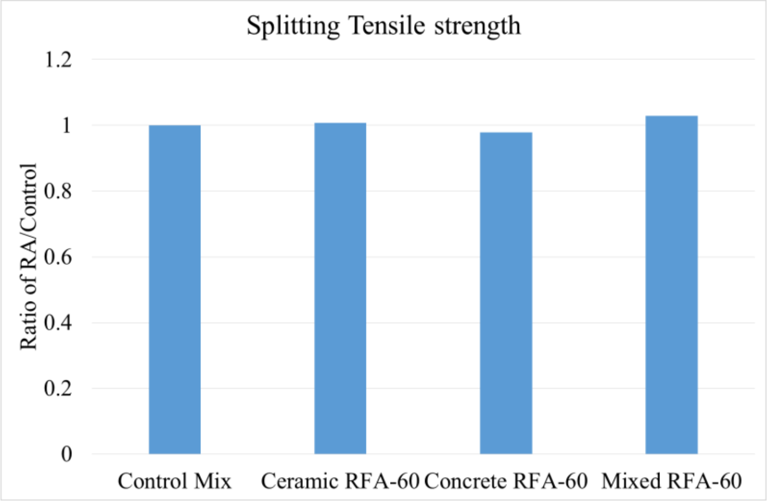


Figure 21. Comparison of splitting tensile strength of Control mix and RA mixes with 100% Portland cement.

It is obvious from the results that the differences were minimal between the control mix and the recycled aggregates mixes. The Ceramic RFA-60 and Concrete RFA-60 have slightly higher splitting tensile strength compared with Control mix and Concrete RFA-60 have the lowest. It can be concluded that the inclusion of recycled aggregates didn't influence the tensile strength significantly. Similar results were obtained by Ju et al. stating that the amount of RFA used had little effect on the tensile strength (Ju et al., 2019). However, Khodair and Bommareddy (2017) affirmed that their results revealed that increasing the recycled aggregates by various percentages greatly reduces the splitting tensile strength (Khodair & Bommareddy, 2017).

4.2.3. Elastic modulus

The table below demonstrates the elastic modulus results obtained after 28 days of curing of the 100% Portland cement mixes and the graph shows the difference between the Control mix and the mixes with recycled aggregates.

Table 16. Elastic modulus results of 100% Portland cement mixes.

	Elastic Modulus (MPa)
Control Mix	42410
Ceramic RFA-60	38236
Concrete RFA-60	36896
Mixed RFA-60	35745

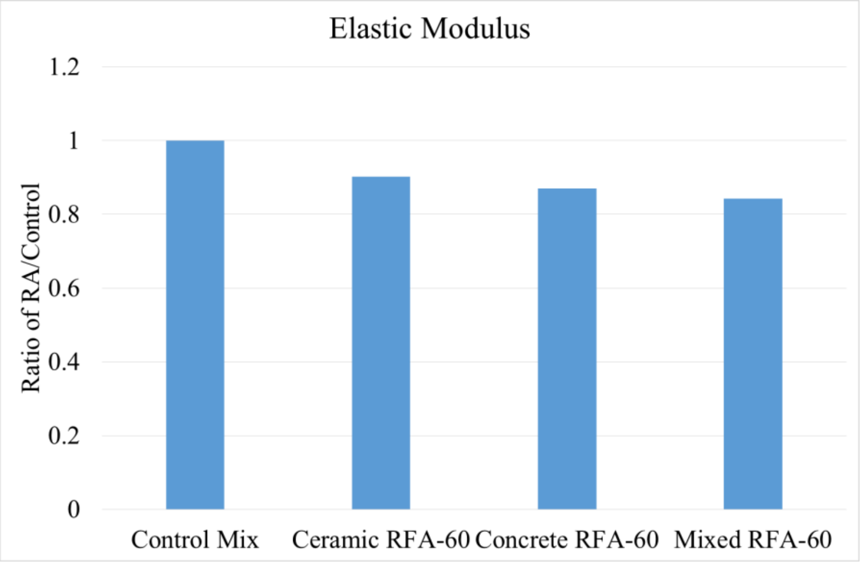
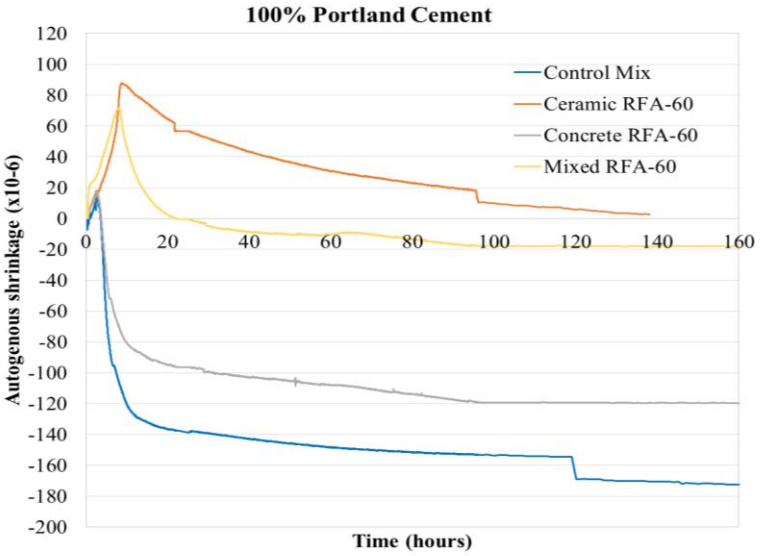


Figure 22. Comparison of elastic modulus of Control mix and RA mixes with 100% Portland cement.

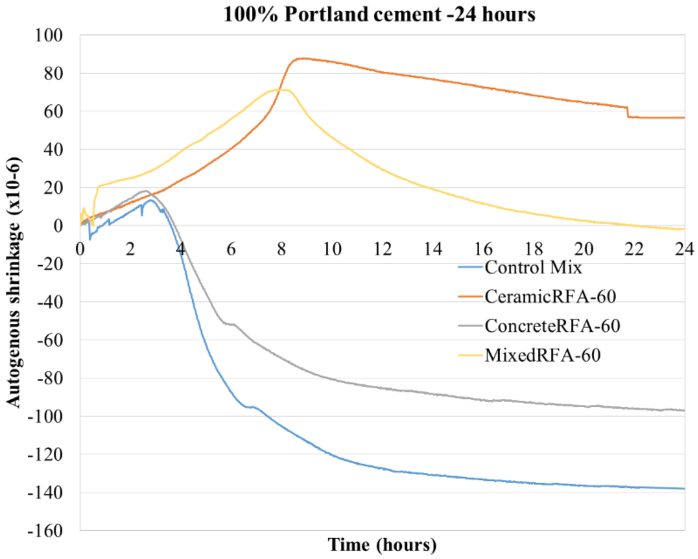
From the values of the results reached, it can be seen that the concretes with recycled aggregates have lower elastic modulus compared with control mix, where Mixed RFA-60 has the lowest elastic modulus (35.7 GPa). Etxeberria and Gonzalez-Corominas (2018) obtained the same result, even though that all of the recycled aggregates concretes had a little lower elastic modulus than the control mixed it was determined that they all had high elastic modulus values of between 35 and 45 GPa, which are within the typical range for high strength concretes (Etxeberria & Gonzalez-Corominas, 2018).

4.2.4. Autogenous shrinkage

Ten minutes after connecting the specimens to the acquisition system, the results of the autogenous shrinkage were obtained. Each figure below illustrates the behavior of each concrete with 100% PC, 30% FA and 50% FA. The figures are divided into two, one representing the autogenous shrinkage during 165 hours (7 days) and one highlighting the results of the early-age shrinkage as in 24 hours.



(a)



(b)

Figure 23. Autogenous shrinkage of the concretes with 100% PC at (a) 7days and (b) 24 hours.

From *figure 23*, it can be noticed that Control Mix and Concrete RFA-60 undergone the highest autogenous shrinkage, while Ceramic RFA-60 and Mixed RFA-60 experienced swelling and expansion during the first hours of the experiment. After 12 hours, Mixed RFA-60 had a reduction until no shrinkage was observed after 24 hours. Similar behavior of the Ceramic RFA-60, the autogenous shrinkage was reduced after swelling until minimal difference was observed after 4 days.

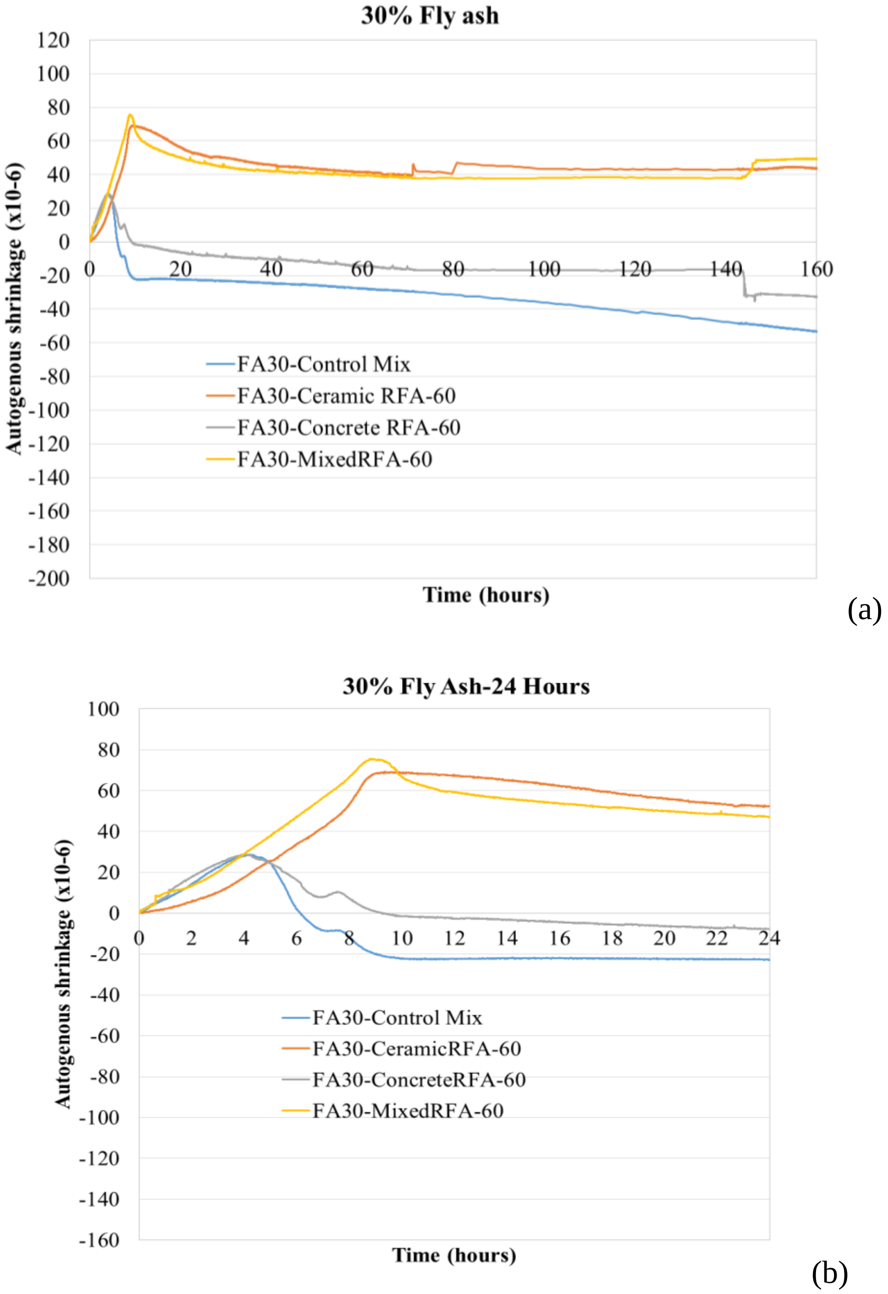
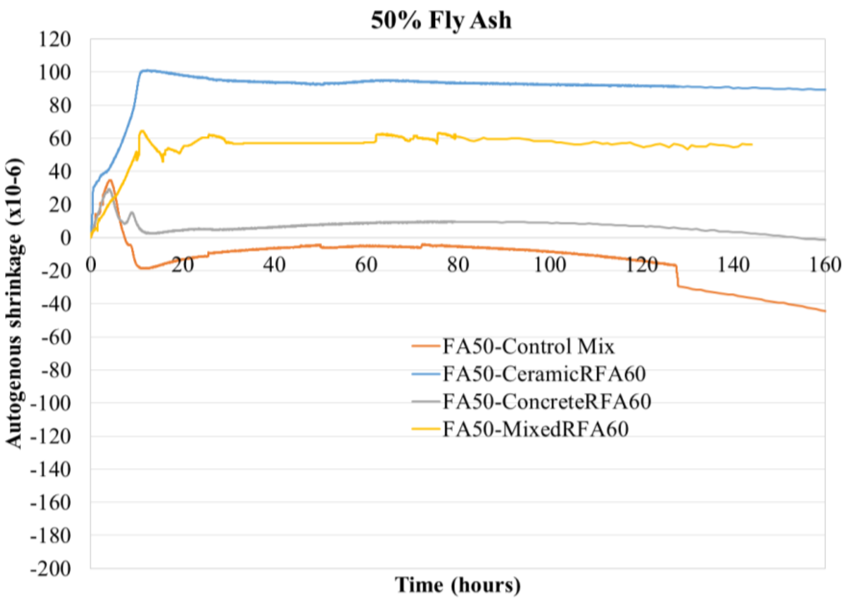
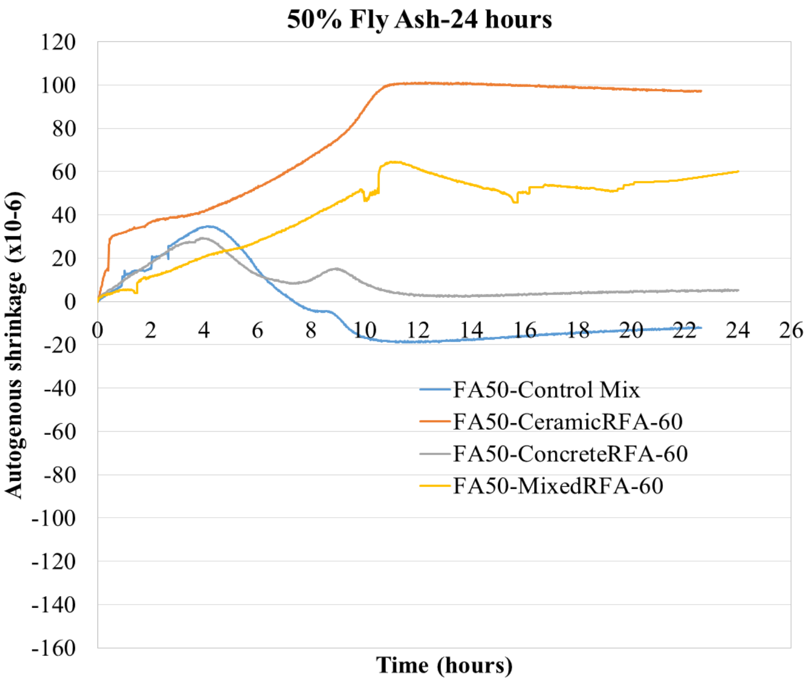


Figure 24. Autogenous shrinkage of the concretes with 30% FA replacement at (a) 7days and (b) 24 hours.

During the first hours in the case of replacing with 30% fly ash, all the specimens experienced swelling and expansion, yet, there was a reduction for FA30-Control Mix and FA30-Concrete RFA-60, until a minimal autogenous shrinkage was observed, $-20x10^{-6}$ and $-16x10^{-6}$ for FA30-Control Mix and FA30-Concrete, respectively.



(a)



(b)

Figure 25. Autogenous shrinkage of the concretes with 50% FA replacement at (a) 7days and (b) 24 hours.

The autogenous shrinkage when using 50% of fly ash wasn’t noticed in FA50-Concrete RFA-60 after experiencing swelling in the first hours. Moreover, FA50-Control Mix had the highest autogenous shrinkage compared with the other concretes. The remaining mixes, FA50-Ceramic RFA-60 and FA50-Mixed RFA-60 endured expansion during the whole 7 days of the test.

To analyze the data above, it can be concluded that in all the three cases the mixes with recycled ceramic and mixed aggregates undergone expansion and swelling, this can be explained by the release of water of the recycled aggregates. Because of the highest water absorption of these two types of aggregates, it allows it to retain and release water for internal curing during cement hydration. The internal curing effect of RA reduces autogenous shrinkage, and the efficacy of RA's internal curing depends on its characteristics (Mao et al., 2021). Ceramic aggregates have a greater porosity and pore interconnectivity than RAC aggregates, allowing for a more faster and simpler transport of water to the paste (Etxeberria & Gonzalez-Corominas, 2018). These results were consistent with those reported in other investigations that used ceramic aggregates as internal curing agents (Etxeberria & Gonzalez-Corominas, 2018). Furthermore, using highly porous aggregates such as recycled ceramic and mixed aggregates, which included more absorbed water than natural aggregates resulted in significant swellings (Etxeberria & Gonzalez-Corominas, 2018). Suzuki et al. (2009) found that results reveal that including recycled ceramic aggregates to reduce autogenous shrinkage resulted in a significant reduction in internal capillary tension in the cement paste and this decrease is related to the reduction in autogenous shrinkage and as a result the risk of early age cracking is minimized (Suzuki et al., 2009).

In addition, from the analysis of the results of this study, it can be deduced that with the increase of fly ash content, the autogenous shrinkage tends to decrease. Termkhajornkit et al., (2005) obtained the same results that autogenous shrinkage was very minor when the fly ash replacement was 50%, however, with smaller replacement level of fly ash it was concluded that autogenous shrinkage was highly influenced by the hydration of Portland cement. The same authors stated that the autogenous shrinkage of OPC mixes was shown to be higher than of high-belite Portland cement mixes, the smaller proportion of C3A or less active Al2O3 in high-belite Portland cement was cited as one reason, it's probable that the same thing happens with fly as-cement mixtures (Termkhajornkit et al., 2005).

4.2.5. Drying shrinkage

The graphs below illustrate the drying shrinkage and the mass loss of the concretes in each case. After 3 days of immersion in water, the specimens were measured and weighed every day for 28 days and for the 56th day.

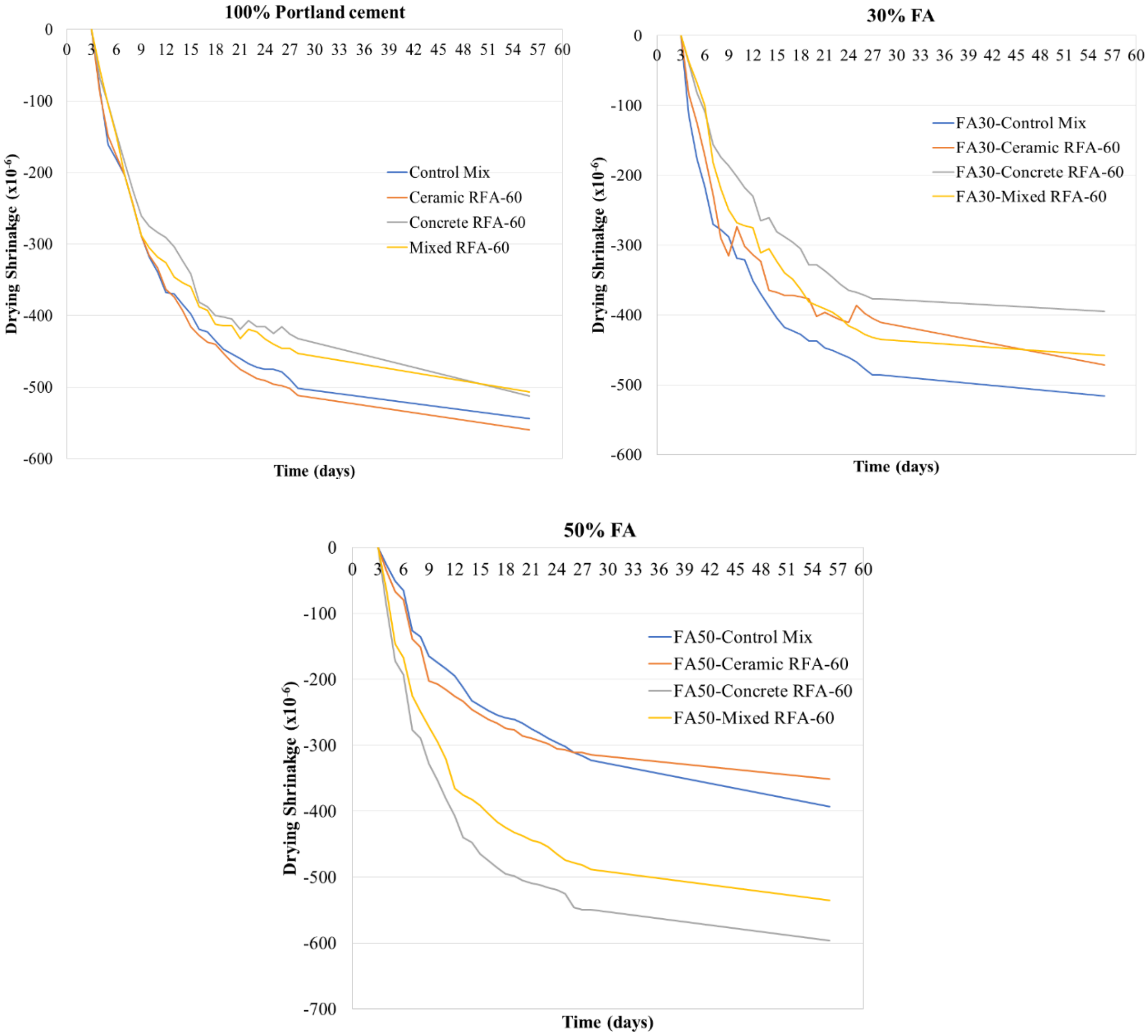


Figure 26. The drying shrinkage of all the concretes produced with 100%PC, 30% FA and 50% FA.

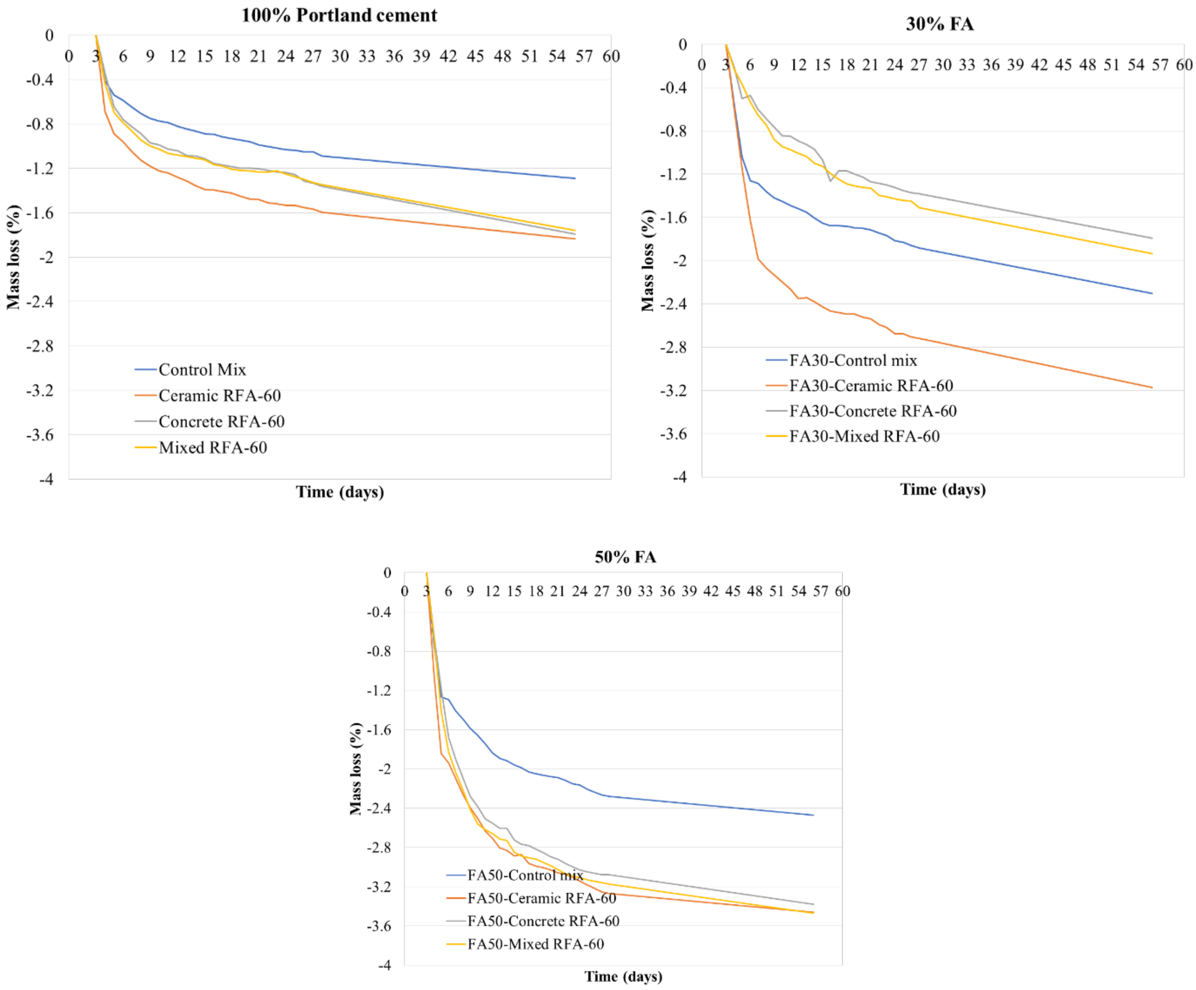


Figure 27. The mass loss of all the concretes produced with 100%PC, 30% FA and 50% FA.

According to ACI, the typical drying shrinkage range varies between -200 and -800 με. From *figure 26*, in 100% Portland cement, the ceramic RFA-60 had the highest drying shrinkage in the test period followed by the control mix. For all the concretes with 100% PC, the strains due to drying shrinkage ranged from -500 to -600 με. When 30% fly ash was incorporated in the mix, FA30-Control mix has the highest drying shrinkage and recycled aggregates concretes smaller. The concretes with 30% FA, had a strain range between -400 and -500 με. However, at 50% FA replacement, FA50-Ceramic RFA-60 have the lowest drying shrinkage between -300 and -400 με, followed by FA50-Control mix in the same range. Besides, mixed and concrete recycled aggregates have highest drying shrinkage in 50%FA in comparison with their behavior in 100% PC and 30%FA, this is due to the high porosity and high water absorption of these two concretes because of the high usage of superplasticizer in the mix with 50% FA.

From *figure 27*, it can be easily noticeable that concrete with ceramic RFA had the highest mass loss in all the cases (100% PC, 30% FA and 50% FA). It can also be seen that as the fly ash content increases the mass loss increases too. FA50-Control mix has the lowest drying shrinkage in 100% PC and 50% FA replacement. Besides, concrete and mixed RA have the same behavior in the three cases and experiencing the lowest mass loss in 30% FA.

It can be concluded that strains of drying shrinkage ranges are in line with the ACI requirements for natural and recycled aggregates concretes. However, the drying shrinkage of recycled aggregates concretes is more than control mixes in 100% PC and 50% FA replacement. Similar results were obtained by (Gonzalez-Corominas & Etxeberria, 2016), the drying shrinkage increased significantly as the content of recycled aggregates increased in the mix compared with natural aggregates concrete. And as the fly content increases, the drying shrinkage decreases. The drying shrinkage of RA-SCC mixes made with binary SCMs is less than that of high-content PC mixtures, according to Guo et al. (2020). The use of pozzolanic materials lowered the amount of cement needed, resulting in a reduction in heat of hydration, owing to the fact that replacing OPC with FA reduced creep and shrinkage in concrete mixtures (Guo, Jiang, et al., 2020). Since drying shrinkage is directly related with the water content, it can be seen that as the amount of water increases in the mixes, the weight loss behavior also increases, since concretes with recycled ceramic aggregates have the highest water content *(Tables 5,6 and 7)*, they experienced the highest percentage of mass loss. Similar deduction obtained by (Gonzalez-Corominas & Etxeberria, 2016) stating that the water evaporation increased as the amount of recycled aggregates used increases and therefore it was more mass loss and the quality decreased.

4.2.6. Chloride penetration test

After 6 hours of the test, the results were obtained and the total charged passed was calculated using the formula mentioned before. The table below illustrates the total charge passed of each concrete at 28 days and 56 days.

Table 17. Results in Coulombs of the total charge passed.

	28 DAYS	56 DAYS
Control Mix	3909	3401
Ceramic RFA-60	4977	3706
Concrete RFA-60	6645	5907
Mixed RFA-60	5604	4799
FA30-Control Mix	2651	1628
FA 30-Concrete RFA-60	4603	2472
FA 30-Mixed RFA-60	3473	2255
FA50-Control Mix	2244	959
FA50-Ceramic RFA-60	2031	797
FA50-Concrete RFA-60	2326	1559
FA50-Mixed RFA-60	2157	1278

Table 18. 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

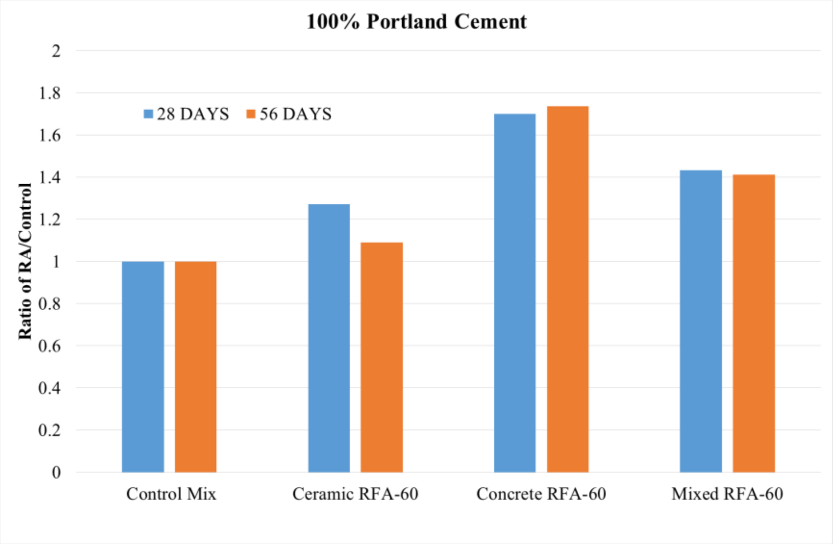


Figure 28. Comparison of control mix with recycled aggregates concretes in 100% Portland cement mixes.

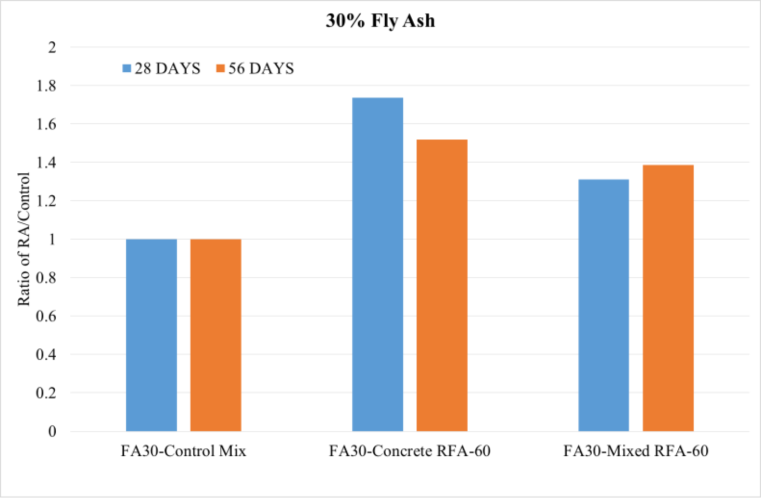


Figure 29. Comparison of control mix with recycled aggregates concretes in 30% fly ash mixes.

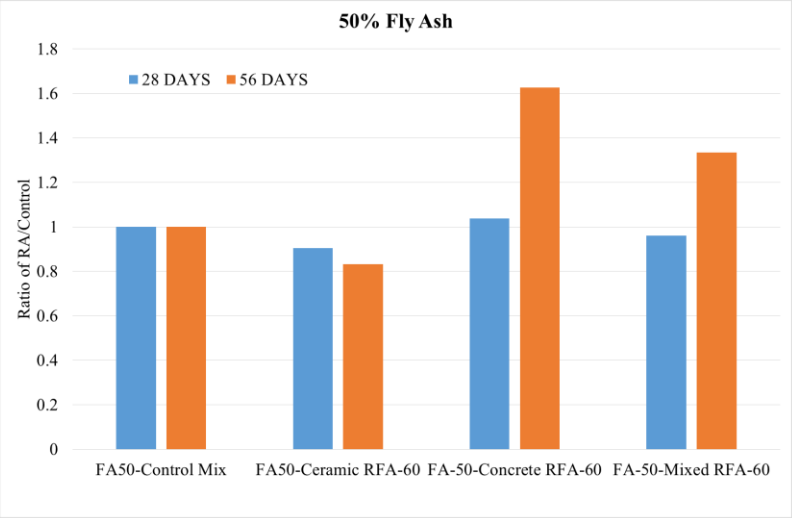


Figure 30. Comparison of control mix with recycled aggregates concretes in 50% fly ash mixes.

From the results obtained, it can be seen that the total charge passed decreased as the curing time increases for all the three cases. In 100% Portland cement concretes the mixes with recycled aggregates have an increase in the total charge passed characterized as high chloride ion penetrability and the control mix as moderate. As for 30% fly ash replacement, the FA30-Control mix have the lowest total charge passed compared with the other mixes, together with FA30-Mixed RFA-60 they both have moderate chloride ion penetrability but at 56 days the FA30-Control mix has a low chloride ion penetrability. On the other hand, at 50% fly ash replacement, the behavior remains the same as the recycled aggregates concretes having smaller total charge passed in comparison with FA50-Control mix. In this case, all the concretes have moderate chloride ion penetrability at 28 days and very low for FA50-Control and FA50-

Ceramic RFA-60 and low chloride ion penetrability for FA50-Concrete RFA-60 and FA50-Mixed RFA-60 at 56 days.

It can be concluded that when using recycled aggregates, the total charge passed is higher, hence, the chloride ion penetrability is higher than control mixes except in the case of 50% FA. Moreover, the mixes with recycled concrete aggregates had the highest chloride ion penetrability with the highest values of the total charge passed in all three cases. Similar results were obtained by (Kou & Poon, 2013), that at all test ages, recycled aggregate reduced the concrete's resistance to chloride ion penetration. In contrast, (Etxeberria, 2014) reported that when compared to conventional concrete, all concretes containing more than 20% ceramic or mixed recycled aggregates had a larger increase in chloride resistance.

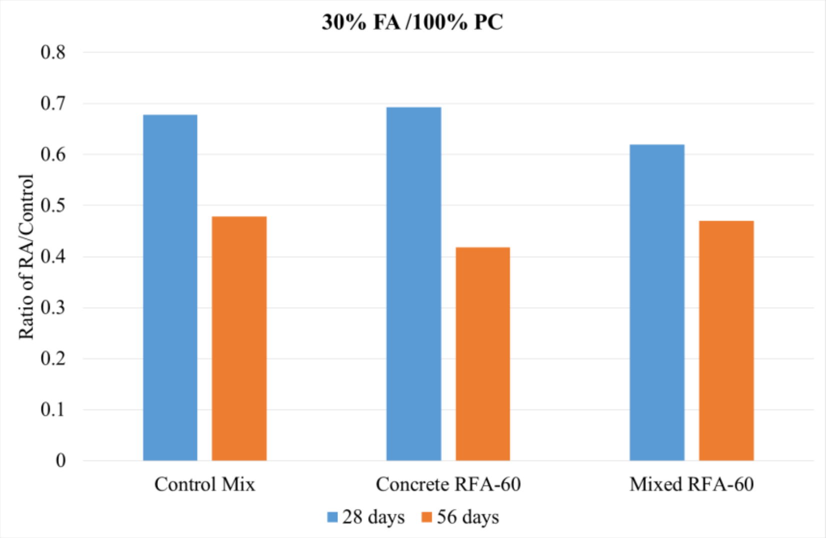


Figure 31. Comparison of the charge passed between 100% PC and 30% FA concretes.

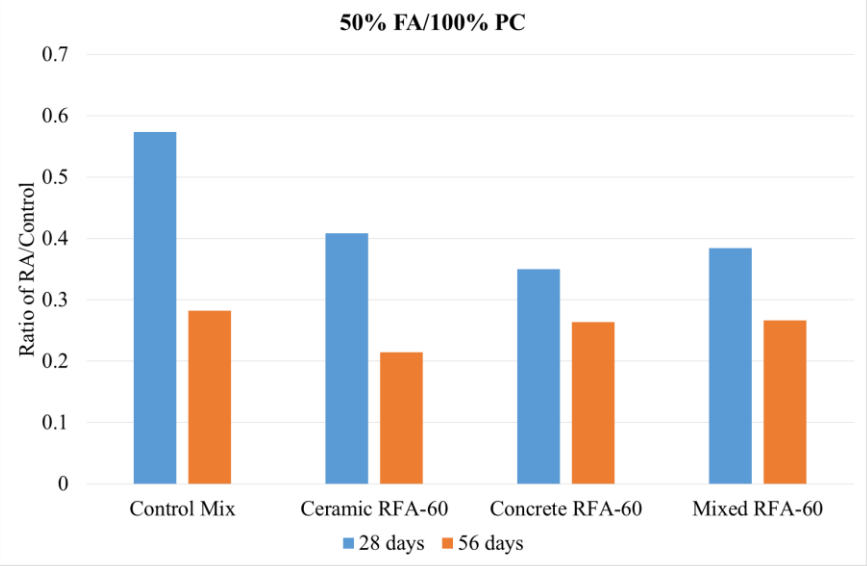


Figure 32. Comparison of the charge passed between 100% PC and 50% FA concretes.

While comparing 30% fly ash replacement to 100% PC, it can noticed that at 28 days the ratio is similar for all the concretes with a slight decrease in Mixed RFA-60. But, at 56 days, the total charge passed has decreased by 20% for Control mix and Mixed RFA-60 and by 30% in Concrete RFA-60.As for 50% FA, the recycled aggregates concretes have a lower ratio than control mix meaning a larger difference than 100% PC recycled aggregates concretes at 28 days. Also, as the curing time lengthens the control mix, concrete RAC and mixed RAC are almost 30% less than 28 days and Ceramic RAC is 20% less.

Overall, as the fly ash replacement increases, the total charge passed decreases in other words the chloride ion penetrability becomes moderate at 28 days and lower at 56 days. As stated in the research of (Kou & Poon, 2013), this is due to the paste's average pore size being reduced and the interfacial transition zone being improved. Also according to (Wongkeo et al., 2014), the chloride chemical binding effect reduces the charges transferred by SCC carrying fly ash, chloride ions usually combine with tricalcium aluminates (C3A) and C4AF to generate calcium chloroaluminates and calcium chloroferrites, both of which are stable forms that reduce the amount of free chlorides accessible. Moreover, in the pozzolanic reactions to chloride physical binding, fly ash causes a rise in calcium silicate (C-S-H) concentration, as a result, the chloride binding capacity of concrete tends to increase as fly ash content increases (Wongkeo et al., 2014).

5. Chapter 5: Conclusions

The influence of three types of recycled aggregates, namely, ceramic, concrete and mixed in the improvement of high-performance self-compacting concrete properties produced with different type of binders (with 0%, 30% and 50% fly ash) was investigated in this study. Following are the conclusions that can be deduced after all the tests have been conducted and the results analyzed:

- In terms of fresh properties, the recycled fine aggregates have less continuous flow compared with conventional concrete but they comply with the EFNARC guidelines requirements. When there is an increase of fly ash, there is less need for superplasticizer and the workability increases.
- There was no significant change in dry density between conventional concrete and RFA concretes however the water absorption increased. As the curing period lengthens, the RFA's water absorption decreases compared to early age curing. The water absorption, when incorporation fly ash increases. However, FA50-Concrete RFA-60 and FA50-Mixed RFA-60 experienced higher water absorption because of the highest use of superplasticizer in the mix leading to a high water absorption and high porosity.
- The compressive strength of recycled aggregates concretes is lower than conventional concrete, except for Ceramic RCA that has the highest compressive strength with a value of 87 MPa, 80 MPa and 76 MPa at 56 days in 100%PC, 30% FA and 50% FA, respectively. However, as the FA content in the mixes increases, the compressive strength decreases for both concretes with and without recycled aggregates.
- The splitting tensile strength of RFA concretes and conventional concrete was quite similar with a 2% increase for Mixed RFA-60 concrete. And the elastic modulus of RFA concretes was 13% lower than conventional concrete but remains in the high-strength concretes range.
- The autogenous shrinkage was more observed in conventional concrete and recycled concrete aggregates, with the reduction of autogenous shrinkage as there was an increase of fly ash. The concretes with ceramic and mixed recycled aggregates checked the feasibility of an internal curing agent by reducing autogenous shrinkage.
- On the whole, the strains of drying shrinkage ranges meet the ACI standards for natural and recycled aggregates concretes. Nevertheless, the drying shrinkage of recycled aggregates concretes is greater than that of control mixes in 100% PC and in 50% FA

replacement because of high porosity. Moreover, when fly ash content increases, the mass loss percentage increases too with recycled ceramic aggregate being the highest since it had high water content in the mix.

- The recycled aggregates concretes had lower chloride resistance than natural aggregates concretes. Also, as the fly ash content increases, the total charge passed decreased by 65% and 43% in 30% FA and 50% FA, respectively at 28 days. In other words, when increasing the fly ash in concrete, the chloride resistance increases.

To conclude, the use of recycled fine aggregates concrete checked the three properties of self-compacting concrete (filling ability, passing ability and segregation resistance) characterizing it with a good workability. However, the mixes had high water absorption and high porosity especially when more fly ash content is used making it a less durable concrete. Moreover, it can also reach a high strength values with and without supplementary cementitious material, especially while using recycled ceramic aggregates. Also, the autogenous shrinkage reduced when utilizing ceramic and mixed aggregates making them a favorable internal curing agent. The chloride ion penetrability of recycled aggregate concretes is low when a large amount of fly ash is used in the mix and the drying shrinkage is more than conventional concrete in 100% PC and 50% FA because of high water absorption capacity.

Future researches

For future research, the use of other supplementary cementitious materials such as silica fume can be investigated in order to increase the initial strength of concrete. As well as, the use of coarse mixed recycled aggregates with 10% absorption capacity as an internal curing agent. Moreover, the performance of different types of admixtures in this type of concrete.

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