Use of Waste Fly Ash from Power Plants for Use in Cementitious Composites for Structural Elements

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Abstract

The construction industry is one of the biggest polluters of the planet. From the extraction and use of raw materials, the construction of structures, the operation and maintenance up to their demolition, the construction industry is responsible for high energy consumption, pollution, creation of 5% of the global CO_2 emissions and a general ecological waste generation and land and resource depletion. After the 1987 UN summit, "sustainable development" was defined as a new target goal engaging countries in "meeting the present needs without compromising the ability of future generations to meet their needs". Sustainability in construction should incorporate elements of economic efficiency, environmental performance and social responsibility by following two distinct paths: use of novel and waste materials and long-term structural performance and durability. Towards this path, the mechanical properties of a new type of composite for construction are examined for fulfilling the above requirements. This type of material is a type of Fiber Reinforced Cementitious Composite (FRCC) made with hybrid Polyvinyl Alcohol Fibers and high amounts of fly ash (>60% of cement replacement), that exhibits advantageous mechanical properties in terms of very large tensile strain capacity and ductility and could be considered the future of sustainable cement based construction. The challenge that remains is to re-establish design rules and analysis procedures specifically tailored to structures made of these materials and promote their use in upgrading and recycling of the existing building environment but also for new constructions. In this direction, material characterization through testing was carried out in order to determine and document the mechanical behavior of this novel ductile concrete to different loading.

1. Introduction

Construction in human history dates back to the prehistoric years, with the use of perishable materials such as leaves, branches, and animal hides and later with more durable natural materials such as clay, stone, and timber. Those materials were used to create from small scale houses to large scale bridges and pyramids, but they always had the advantage since being natural, they could be either reintegrated in the environmental through disintegration, or they could be re-used; in no case, however, were they waste, and ecologically harmful at that. The first use of synthetic materials such as concrete appeared in the Roman era in the form of a hydraulic lime mortar and the addition of volcanic ash (a pozzolan that had the ability to harden under water). But until the nineteenth century and the industrial revolution, synthetic materials were only used for special and important structures and not in a broad scale. After the industrial revolution the use of reinforced concrete became widely used, and was used for a great range of project, not only in special constructions but also in small private residences. The use of steel and concrete (Reinforced Concrete) was massively produced from that point onwards, but in no case could the proponents of RC concrete foresee the problems created by its wide range use to the future generations and the planet.

As it was promoted by the capitalist model the flow of production would follow a linear approach from the harvesting of the essential natural resources, the creation and use of synthetic products and their disposal in landfills. This approach has also been used in the construction industry. Materials are first extracted from natural resources: lime and clay for the production of cement, coarse aggregates are produced from crashed stones, sand, steel as an alloy of iron and carbon. Those materials are then mixed with water and the result of the chemical reaction is a formidable solid material which is used extensively throughout construction. Due to the environmental effects (carbonation), natural phenomena (earthquakes), and climate conditions (rain, snow, wind, sea cost chlorides) structures, especially those with no great importance [1], are designed and built for a service life in the range of 50 years. In the end of the service life period, those structures are in most cases turned into

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construction waste, waste that may contain lead, asbestos or other hazardous substances and those are thrown on wastelands. The first environmental movements in the 70s, that followed the energy crisis, triggered the concept of developing "closed-loop" approaches to the production process, mimicking and integrating the symbiotic biological ecosystems they exploited [2], [3], [4]. In the years after, the theory of "The Treadmill of Production (ToP)" as developed by Schnaiberg [5] offers an explanation of the expansion of environmental problems in the modern era by relating advances in technology and the drive for production and consumption synergistically, leading to a cycle of production necessitating more production and argues that environmental problems cannot be solved in such a system, since growth puts ever-increasing demands on the environment by extracting natural resources and generating pollution. Thus, achieving environmental sustainability requires radical restructuring of the political economy and a move away from growth dependence.

Other than the waste materials produced at the end of the life time of the structures, the construction industry is also responsible for CO_2 emissions. This year's COP21 United Nations Conference on climate change has issued a resolution to limit the rate of global warming through a global reduction of the responsible emissions. The production of Portland cement is accountable for 5% of global CO_2 emissions, owing to the extreme heat required for cement production: a ton of cement requires 4.7 million BTU of energy, equivalent to about 180kg of coal, and generates nearly a ton of CO_2. Cement's production is growing by 2.5% annually, and is expected to rise from 2.55 billion tons in 2006 to 3.7-4.4 billion tons by 2050 with the equivalent amount of CO_2 emitted to the environment [6]. In addition to the emissions, cement and concrete production is responsible for the excessive consumption of lime, clay and burning energy required in the process, also for the use of water and gradated crushed aggregate materials.

According with the 1987 UN definition, "sustainable development" is "meeting the present needs without compromising the ability of future generations to meet their needs". With the increasing development of the build environment throughout the globe and the trends of people in the "developing" world to adopt a consumer-driven lifestyle, the question of concrete's sustainability gains new perspective. Recycling in general (i.e. of aggregates) is pursued as one alternative at the cost of yet more energy and resources in order to process materials to a re-usable state.

The recent developments in sustainable and ecologically friendly design of structures has led to the need of reducing materials extracted from the earth (aggregates) and water content of concrete and cement that produces carbon dioxide, and replace them with recycled materials or byproducts. One of the most promising attempts for sustainable development for concrete is the use of fly ash (FA), a byproduct of the energy industry that otherwise ends up in wastelands creating lots of environmental problems. Depending on its classification fly ash may be used in concrete as a cement replacement at a maximum amount of 40% as per ACI [7]. Fly ash acts in the cementitious composites as a pozzolan, reacting chemically with calcium hydroxide and forming compounds possessing cementitious properties. Shrinkage and tensile strength and deformation capacity are enhanced by means of synthetic fine-diameter fibers leading to truly innovative cementitious materials with impressive ductility in tension, sustaining their tensile strength up to strains that are 200 times greater than the cracking strain of normal concrete.

Cementitious materials are considered to be brittle due to the crack initiation that occurs internally during hydration, even prior to the application of any external load; cracking concentrates particularly at the point of contact between gel and aggregates due to the unilateral growth of binding, and is owing to the stress concentrations due to different material stiffness. Fibers, if bonded properly, can bridge these cracks and transfer the loads, delaying brittle failure by connecting and widening of the cracks. At the same time, through proper mix design stress concentrations are minimized by eliminating any form of coarse aggregate from the cementitious mix design. A large content of fly ash delays stiffening of the mix necessarily imparted by wetting of the large surface area of the fibers, also assisted by the addition of superplasticizer.

A holistic approach by world governments should include taking into consideration that we are not the last human generation on the earth nor the only inhabitants of this planet. The ever increasing number of aged structures that are in the end of their service life, or have accumulated extensive damage, or no longer meet the Modern Codes' provisions for earthquake resistance or durability, may be up to 70% of the built environment in the developed countries. This enormous percentage of existing old structures requires great expenditure for rehabilitation and maintenance. Roughly fifty percent of the total expenditure for construction is needed for maintenance and repair in many industrial countries [8].

2. Use of Waste Products for concrete: the case of fly ash

2.1 Origin and properties of fly ash

The first research concerning the use of fly ash as a supplementary material for concrete was published in the beginning of the 19th Century [9]. Fly ash is a by-product of burning pulverized coal in electricity-generating stations. It is the residue that is carried away by the flue gases and it is collected by separators. The composition of the raw materials that are burned (anthracite, bituminous, sub-bituminous and lignite) and the burning conditions within the generating stations may give different mineralogical and chemical composition to the produced fly ash at different stations. Independent of the differences all fly ashes include substantial amounts of silicon dioxide (SiO_2) (both amorphous and crystalline), aluminum oxide (Al_2O_3) and calcium oxide (CaO), the main mineral compounds in coal-bearing rock strata. They also may include one or more of the following elements or substances found in trace concentrations (up to hundreds ppm): arsenic, beryllium, boron, cadmium, chromium, hexavalent chromium, cobalt, lead, manganese, mercury, molybdenum, selenium, strontium, thallium, and vanadium, along with very small concentrations of dioxins and PAH compounds [10], [11]. In the beginning of the last century fly ash was released into the atmosphere but later air pollution control standards required that it be captured prior to release, since that procedure created environmental and health concerns. New legislation has led to a reduction in the amount of fly ash emissions to less than 1% of ash produced. In the United States fly ash that is captured from emitting is generally stored at the power plants or placed in landfills. This procedure was questioned in Dec. 22, 2008, when a containment dike ruptured at Kingston Fossil Plant near Kingston, Tenn., and sent 4.2 billion L of coal fly ash slurry over 122 hectares of surrounding land, damaging homes and flowing into nearby rivers. This spill was the largest fly ash release in U.S. history. Cleanup costs were estimated to run anywhere between $525 million and $825 million, not including potential long-term cleanup [12]. Therefore, there is a major need in recycling of the total amount of fly ash produced for a series of reasons such as contamination of the air, use and contamination of landfills, dangers of spilling and contamination of water basins, risks not only for human but also for the environment.

The most prevalent use of fly ash reported until now, and the one that holds promise to absorb most of the produced fly ash, is its use in concrete as a cement replacement. Due to its chemical composition fly ash may be used in concrete contributing to its mechanical properties either by hydraulic or pozzolanic activity, or both. A pozzolan is a siliceous or siliceous and aluminous material which, in itself, possesses little or no cementitious value but which will, in finely divided form and in the presence of water, react chemically with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties [13]. Fly ashes with high calcium content also exhibit hydraulic properties. Wide range utilization of fly ash in concrete started in the middle of the previous century after the pioneer work done at the University of California, Berkley [14]. Nowadays Standards have been accepting the use of percentages of up to 30% of fly ash as cement replacement, while this level may change according to the special features of each construction's specifications. For example, levels of up to 50% of cement replacement with fly ash have been reported in massive structures such as dams or foundations for temperature control.

Standard specifications for the classification of fly ash depend upon different characteristics if the North American Standards or the Canadian standards are taken into consideration. In North America [15] fly ash is divided based on its type of origin and composition (See table 1) while the Canadian Standard (CSA) [16] separates fly ash in three classes based on their calcium content (See Table 2). The amount of CaO used in CSA indicates whether the fly ash will only have pozzolanic properties (<8%) or it will also have hydraulic properties. Fly Ashes with high amounts of CaO may produce concrete with moderate strength even without any use of cement.

TABLE 1 Chemical Requirements as per ASTM [15]

Class	SiO_2+Al_2O_3 +Fe_2O_3 %	SO_3 max, %	Moisture content %	Loss of ignition %
N—Raw or calcined natural pozzolans that comply with the applicable requirements for the class as given herein, such as some diatomaceous earths; opaline cherts and shales; tuffs and volcanic ashes or pumicites, calcined or uncalcined; and various materials requiring calcination to induce satisfactory properties, such as some clays and shales.	70.0	4.0	3	10.0
F—Fly ash that meets the applicable requirements for this class as given herein. This class of fly ash has pozzolanic properties.	70.0	5.0	3	6.0
C—Fly ash that meets the applicable requirements for this class as given herein. This class of fly ash, in addition to having pozzolanic properties, also has some cementitious properties.	50.0	5.0	3	6.0

TABLE 2 CSA specification for FA

Type F	<8% CaO
Type Cl	8-20% CaO
Type CH	>20% CaO

In Figure 1 the calcium content (as per CSA) is compared to the sum of the oxides (SiO2 + Al2O3 + Fe2O3) (as per ASTM) for the same fly ashes. All fly ashes that meet CSA Type F or Type CH would be classified as Class F and Class C by the ASTM C618 [15]. However, most fly ashes that meet CSA Type CI could be classified by ASTM as either Class C based on the coal source or as Class F based on the sum of the oxides [17].

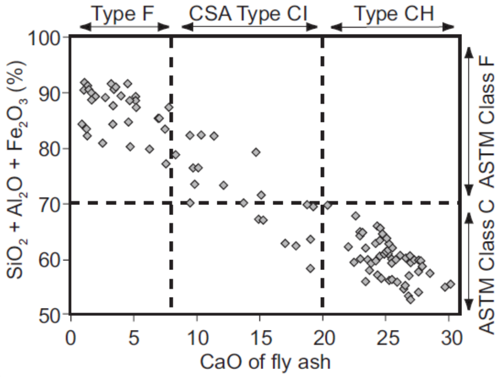

Fig. 1 Relationship between calcium oxide content and the sum of the oxides (SiO_2+Al_2O_3+Fe_2O_3) for 110 North American fly ashes [17].

2.2 Benefits of Fly Ash in concrete

Fly ash has been used up till now as a cement replacement for almost one century and its advantages and disadvantages have been thoroughly examined throughout the globe. Although fly ash may in some occasions be used in great percentage as cement replacement, the North American Standards [18] have placed an upper bound to its use from the wider market. Class C fly ash is recommended to be used as a cement replacement in the order of 20-35%, while class F fly ash only between the limits of 15-25%, even though research in the last years has expanded to the use of High Volume Fly Ash (HVFA) composites, consisting of more than 70% of fly ash as cement replacement [19]. Benefits from the use of fly ash in concrete may be categorized in those which refer to the fresh mix state and those related to the hardened mix properties.

Fly Ash consists of glass spheres from 0.01-100μm in size, with a typical particle diameter in the order of 50μm. For the fresh state of concrete, if fly ash has high fineness, due to the spherical shape of its particles it reduces friction amongst all particles and therefore increases workability. Consequently water content of the composite may be decreased with a gross approximation reported by Thomas [17] to be a reduction of water of 3% for every 10% cement replacement by fly ash. This water reduction also increases the composite's strength. The spherical shape of the particles also increases workability and consolidation and reduces segregation. In the case of HVFA concrete the improved rheological properties make it perfect for use in self compacting concrete [20]. Bleeding of concrete is a form of segregation, where the lighter water rises above all other materials in the mix, while the solid components of concrete do not have the ability to withhold it. Due to the decreased water content the bleeding of composites with fly ash decreases.

One of the most important reasons for the use of fly ash in concrete is the low setting rate and the reduction of the internal heat produced thereof, that in mass concrete constructions would initiate autogenous shrinkage and internal microcracking. Examples of mass replacement of hydraulic cement with fly ash in order to reduce generation of heat during hydration in construction are that of the Thames Barrage in the United Kingdom and the Upper Stillwater Dam in the United States [7]. This may also count as a disadvantage if there is the necessity of having higher strengths achieved in early ages. Even more in cold weather the setting time increases, delaying significantly the initial and final setting time. The higher the calcium content in fly ashes the more of an increase of the setting time is observed, as compared with the low calcium content fly ashes, due to their increased hydraulic properties.

As it is seen this delay in setting time affects the properties of the hardened concrete. There might be a lower compressive strength if concrete is tested at early ages, but at later stages fly ash continues to react, with the hydration products resulting at higher strengths and a denser microstructure, if the curing is sufficient. This denser microstructure also affects the permeability of concrete containing fly ash to water and gas convection and therefore increases its durability. Additionally low calcium content fly ashes can control alkali-silica reaction, due to the reduction of alkali hydroxides in the presence of fly ash.

3. Use of Fibers for durability and strengthening

Concrete's main disadvantage is its low flexural strength and ductility in tension. Cracks form due to various reasons causing numerous problems that tend to progress and accumulate over time. These are due to carbonation and corrosion of the concrete and reinforcement compromising the remaining strength of concrete members. In ancient times it was customary to use fibers from straw in the mud bricks enhancing the flexural capacity of the units. This technology is now used for concrete. Currently, the state of the art in research revolves around the use of short discontinuous fibers in self-consolidating, fine-aggregate cementitious mixes. The objective is to enhance the composites' flexural strength, ductility and toughness and furthermore to limit the width of cracks thereby eliminating further deterioration due to environmental effects. Fibers used are of different shape, material and/or composition. Most popular up till now are metal fibers, polyvinyl-alcohol (PVA) fibers, polypropylene (PP), UHMW polyethylene (PE) and carbon-fibers. Fiber reinforced cementitious composites (FRCC) are classified according to their mechanical performance in tension. They are distinguished in strain softening and strain hardening. Strain softening means that deformation is concentrated at one single crack and the area around it. In the case of strain hardening, deformation occurs within multiple parallel fine cracks with elastic stretching of the material between them.

Each type of fiber develops a different type and intensity of binding with the surrounding matrix and the final product´s characteristics are greatly affected by this property, referred to hereon as *specific bond*. In the present investigation PVA fibers have been used. It has been shown in previous studies that the coating on PVA fibers increases the dispersion of the hydrophilic fibers and the final ductility of composites by changing the interface bond properties between the fibers and the matrix [21],[22].

SHCC are able to control crack widths, by the formation of multiple cracking rather than localization of deformation at one single crack. This phenomenon is resembled to tension stiffening, as fibers bridging the cracks in relation to the steel reinforcement, transfer the tensile loads through interface bond [21]. Crack control plays an important role in limiting chloride or other deleterious gas penetration in the matrix and the accumulation of critical concentration of these substances on the surface of steel reinforcement. The denser microstructure due to the use of fly ash, as well as crack width restriction of the fibers increase the resistance of these types of SHCC and evidently their durability [23]. Şahmaran and Li [24] studied chloride penetration by immersion tests and found that the SHCC had reduced chloride penetration as compared to mortar in uncracked specimens, while in the case of cracked beams under four point bending, the crack width was found to be insensitive to the deformation level and therefore the chloride diffusivity was almost constant in the case of SHCC in contrary to the plain mortar where it increased exponentially with increased deformation.

In comparing reinforced beams made of mortar and SHCC, Miyazato and Hiraishi [25] exposed beams of the two materials under accelerated chloride while maintaining the beams under constant load. The same load made one single crack in the mortar beam with 0.3mm width while it made several cracks of 0.1mm in the case of the SHCC matrix. The conclusion was that the SHCC beam showed reduced corrosion rate. Also in the SHCC beams spalling is unlikely to occur not only due to the reduced rate of corrosion but also due to the fibers that bridge the cracks surrounding the reinforcement, providing passive lateral confinement to expansion. Crack widths are as shown by Li and Stang [26] independent of member size and an intrinsic material property, and by this SHCC have high material resistance to the widening of the cracks, a parameter that additionally restrains drying shrinkage and cracking.

The first combination of fly ash with fiber reinforced composites was made by Song and Zijl [27] in an attempt to decrease the cost of SHCCs and another way to reduce the chemical bond between the PVA fibers and the cementitious matrix. The authors tested mixes with various percentages of cement replacement with FA and came to the conclusion that a FA content beyond 30-40% does not significantly influence the strength value of the tested mixes, since FA beyond that range does not participate in the hydration process, but it behaves as a filler material or aggregate.

The availability of cementitious materials with ductility in tension is an opportunity for the development of alternative designs that enable significant economy in steel reinforcement, for more durable and sustainable structures. However, to incorporate these materials in modern codes there is an outstanding need to determine the properties of these new types of composites. In the present research, which includes both analytical and experimental components, the focus is placed on interpretation of the behavior of these types of composites under various loads such as tension, compression, flexure and direct shear (push-off tests), a first step into drawing design recommendations for structural members subjected to these states of stress.

4. Experimental program

4.1 Materials

The target of the research was to examine the mechanical properties of a self-consolidating cementitious mix, with high percentage of FA replacement and its improved performance with the addition of fibers. The mix design selected was ECC-M45 [28] suitable also for large scale casting. The materials and quantities were adjusted to the local available options. Thus, the cement used was Portland Composite Cement En 197-1 Cem Ii / A-M (L-S) 42.5 R. This type of Blended Cement is produced using pure calcite limestone and is more impermeable and dense as compared to OPC, with a higher degree of workability and reduced plastic shrinkage. The compressive strength of this particular cement is at 28 days equivalent to that of 42.5 R OPC and superior at 2 and 7 days. Silica sand (>95% Si) used had a maximum grain size of 300μm. The FA was of type F. In the present investigation 12mm long, 39μm diameter PVA fibers were used. The nominal tensile strength was 1600MPa, Young's Modulus was 40GPa and the density was 1300kg/m^3. The fibers used were specially coated. Mix details for the two types of composites with and without the use of fibers are listed in Table 3. Steel reinforcement comprised of 6 and 8mm bars with 200MPa Modulus of Elasticity, 500MPa with ribs for the 8mm bars and 300MPa for 6mm-diameter bars without ribs.

Table 3: Mixture proportions

Mix	Cement	Fly Ash	Sand	Water	Super Plasticizer	Fibers
SHCC	1.00	1.20	0.80	0.60	0.017	2% (per volume)
HVFA	1.00	1.20	0.80	0.55	0.012	-

4.2 Specimen Design

Tests were carried out on a series of specimens to determine the mechanical properties of the mix with (SHCC) and without the use of fibers (HVFA) under various loading. The tests comprised of direct tension, uniaxial compression, split cylinder tests, four point bending with and without steel reinforcement and push off tests. Three identical specimens were tested for each type of test and mix design. Specimens were tested at the age of 100 days, in order to acquire the long term mechanical properties of the composites, since the presence of fly ash, as well as the coating of the fibers, change the interfacial bond properties between the fibers and the matrix and therefore the multiple cracking phenomenon, thereby altering the material's strain capacity [21].

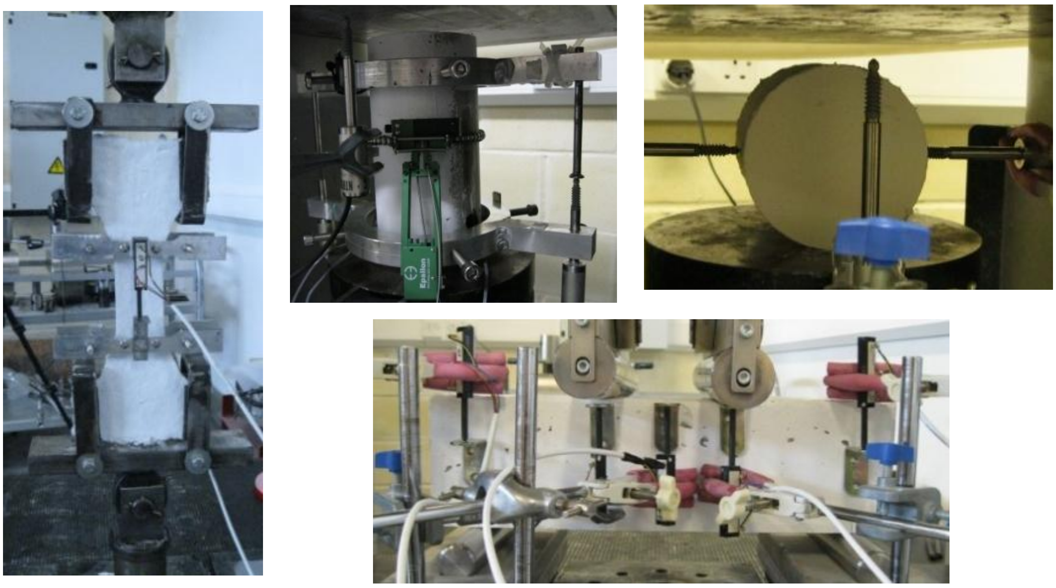

Fig. 3 (a) Uniaxial tensile test coupon and setup, (b) Uniaxial compression test setup with measuring devices (c) Loading setup for split cylinder test and (d) Test setup and LVDTs for four-point bending

The dimensions of all tested specimens are recorded in Table 4, as well as the displacement controlled loading rate. Displacement controlled direct tensile tests were carried out on dog bone specimens with the testing setup as proposed in previous studies [29]. Geometric details of the reinforcement for the beams under four point bending are given in Figure 4. Specimen identification code in Table 4 is as follows: In example "SH-4PB" defines the beam without any steel reinforcement, the second symbol "R" defines the existence of longitudinal (flexural) reinforcement and the third symbol "S" defines the existence of shear reinforcement. The direct shear behavior of the mixes was investigated with the use of uncracked push-off specimens. The specimens detailing in the case of stirrups is as shown in Figure 4 (c), with a shear plane area of 100x200=20000mm^2 as determined from previous research [30], [31]. Parameters of the investigation were: a) the mix design – the use or not of fibers and b) the presence of steel stirrups crossing the shear plane.

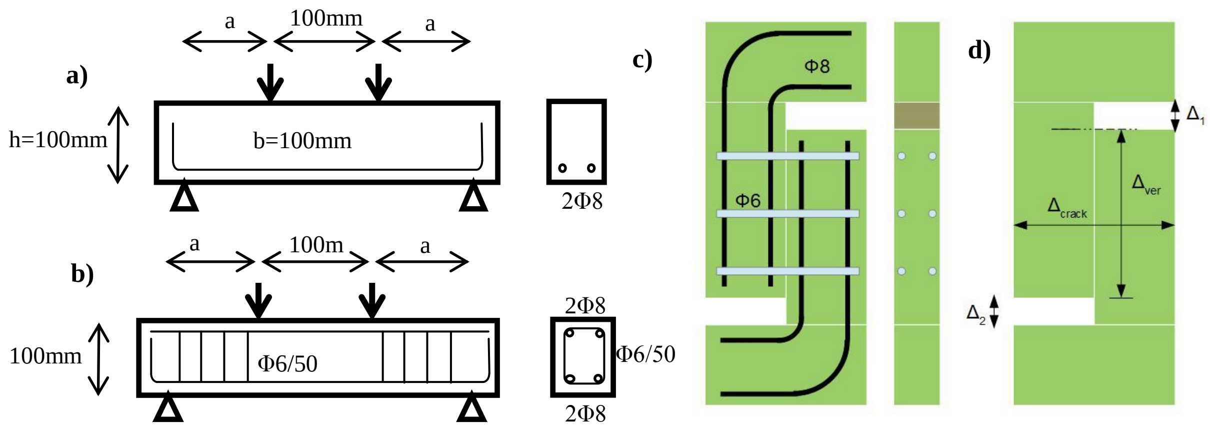

Fig. 4 Test configuration for four point bending and reinforcement details for (a) beams with flexural reinforcement placed so as to increase the magnitude of shear demand in the beam shear spans, (b) beams reinforced with longitudinal bars and stirrups for shear strength and (c) Push-off specimen steel reinforcement, (d) definition of deformation for graphic presentation

Table 4: Specimen designation – test type – dimensions – rate of loading

Specimen designation	Test	Material	Dimensions	Displacement rate	Reinforcement
FA-T	Uniaxial tension	HVFA	25x50	2.5μm/s	-
SH-T	Uniaxial tension	SHCC	25x50	2.5μm/s	-
FA-C	Un. compression	HVFA	100x200	1.5μm/s	-
SH-C	Un. compression	SHCC	100x200	1.5μm/s	-
FA-S	Split	HVFA	100x100	0.50 mm/min	-
SH-S	Split	SHCC	100x100	0.50 mm/min	-
FA-4PB	4 point bending	HVFA	100x100x300	1.5μm/s	-
SH-4PB	4 point bending	SHCC	100x100x300	1.5μm/s	-
SH-4PBR	4 point bending	SHCC	100x100x300	3μm/s	2Φ8
SH-4PBRS	4 point bending	SHCC	100x100x300	3μm/s	2Φ8+Φ6/50
FA-P	Push off	HVFA	100x200	7.5μm/s	-
FA-PR	Push off	HVFA	100x200	15μm/s	6Φ6
SH-P	Push off	SHCC	100x200	15μm/s	-
SH-PR	Push off	SHCC	100x200	15μm/s	6Φ6

5. Results from the experimental program

5.1 Direct tensile properties

The initiation of cracks in concrete is governed by its tensile properties, therefore it is one of the most important parameters that would need to be determined prior to any analysis of a concrete member. Even though it is rather difficult to perform uniaxial tension tests on normal cement composites, in the case of fiber cementitious composites this becomes more possible. In the case of the HVFA mix (i.e., plain matrix) the three samples that were casted for uniaxial tension, cracked during their de-molding. The SHCC mix on the other hand demonstrated strain hardening response in uniaxial tension as illustrated in Fig. 5 (a). Strain was calculated as the elongation measured by the equipment mounted on the specimens' two opposite sides and divided by the gage length of 100mm. During the formation of multiple cracks, stress capacity of the cross section increased. Past the yield point multiple cracks form and fibers bridging the cracks elongate from the stress they transfer but simultaneously they also pull-out from the matrix at the crack locations. Formation of cracks saturates the full length within the measuring range and even spreads outside that, on the wider cross sections of the specimen. Beyond a limiting strain value which depends on the competition of interfacial bond and the tensile strength and stiffness of the fibers, new cracks cease to form and crack localization is evident (this point defines the maximum tensile stress f_{tmax} and respective strain ε_{tmax}); as bond strength increases with age due to ongoing hydration, there is a growing tendency with age, of the occurrence of increasing crack-widths and local fracturing of fibers witnessed by a marked reduction in the available strain ductility ε_{tmax}.

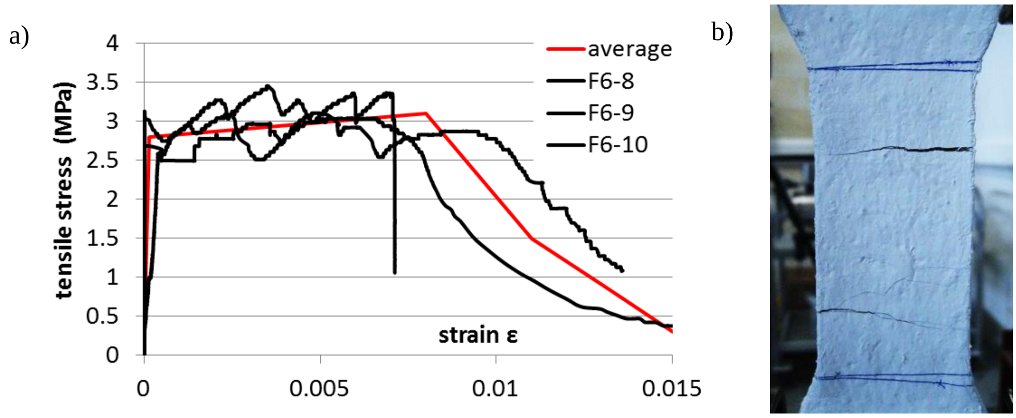

Fig. 5 (a) Stress-strain diagrams and (b) multiple cracking of direct tension test on SHCC

The actual crack elongation after the strain softening behavior occurs is as measured in the experiment ε=0.016-0.008=0.008 (mm/mm) or total crack widths w_{usoft}=0.008x100=0.8mm. Ultimate strain of a single fiber at rupture is calculated as 1600/40000=0.04 (mm/mm). If the full length of the fiber was deformed with stress being constant over the length of the fiber then deformation of the fiber would have been 0.04*12=0.48mm. If compared to the actual crack elongation (0.8mm) this estimated value cannot be used to explain the full crack width therefore leading to the conclusion that crack width consists of partial pull-out of the fibers and partial elongation of the fibers due to strain. The fracture energy G_f is the area under the stress-crack opening curve in the strain softening branch past the ultimate stress. For the SHCC is calculated as G_f=1065 N/m a value much greater than the expected one for ordinary strength mortars and concretes which was found to be in the order of 50N/m and 130N/m respectively [32].

5.2 Uniaxial compression results

Figure 6 (a) compares the stress - axial strain - lateral strain diagrams obtained from compression tests conducted on the specimens with the use of fibers (SHCC) and of the same matrix without the fibers (HVFA). The compressive strength of the latter reaches 58MPa as maximum from the three tested samples and 50.37MPa as the mean average, but with the addition of fibers the strength decreases to a maximum obtained value of 54.35MPa and 48.98MPa as average. An increase by more than 30% occurred in the axial deformation that corresponds to peak load as compared to the corresponding values for plain mixes in the case of the matrix with the fibers (average strain at peak stress from -0.0032 for the HVFA to -0.00459 for the SHCC), as well as a stable descending branch. Based on the uniaxial compression experimental results of fiber reinforced cementitious composites as shown in Figure 6 multiple cracking is evident all around the specimen. No evidence of deterioration or collapse is exhibited even after 60% drop of the postpeak capacity under compression. In the case of the plain matrix deterioration is exhibited along with sudden collapse of the specimen if no confinement is used.

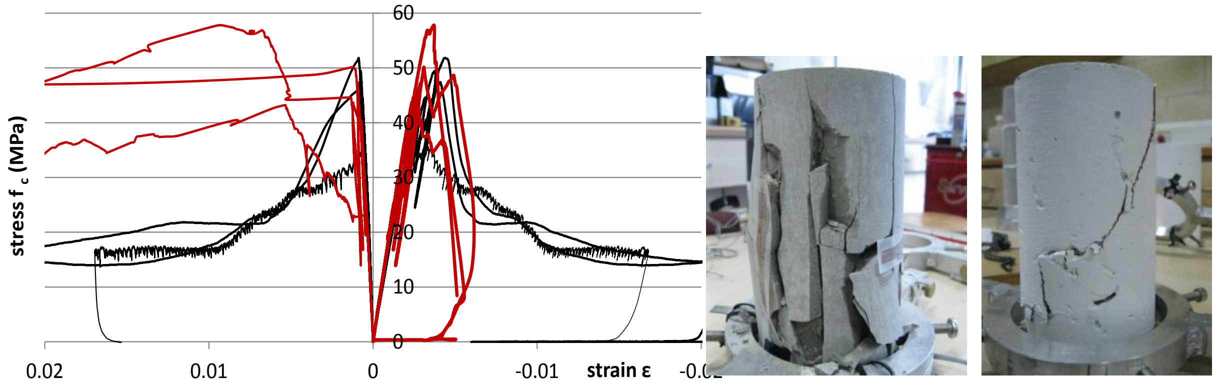

Fig. 6 (a) Stress - axial/lateral strain diagrams under compression of HVFA and SHCC mixes, (b) failure cracks for HVFA (c) failure cracks for SHCC

The use of confinement (addition of fibers) changes the type of failure. Lateral deformation is responsible for the rate of descend of the post peak branch. Fibers mobilized in the lateral direction can bridge cracks, transferring load and limiting lateral expansion of the cylinder under compression. This is evidenced by the restricted growth of post-peak lateral strain of the mix with fibers as compared to the plain concrete specimens. The stress-strain curves suggest that past the peak load, concrete with fibers behaves as if internally confined. The intensity of confinement is directly related to the materials' stress-strain behavior under tension.

5.3 Split cylinder test results

Cylinder splitting is a more straightforward method to determine the tensile strength of normal-strength concrete [33]; in this arrangement the diametric surface is loaded in direct tension. In the case of strain hardening composites multiple cracks are expected to open parallel to the loading axis, with the fibers bridging the cracks and transferring load over a wider area. In the case of SHCC it was found that the fibers confer pseudo-elastoplastic response to the matrix by controlling the crack propagation. In addition, the pattern of stress distribution shape is not affected by material softening, contrary to what occurs in flexure.

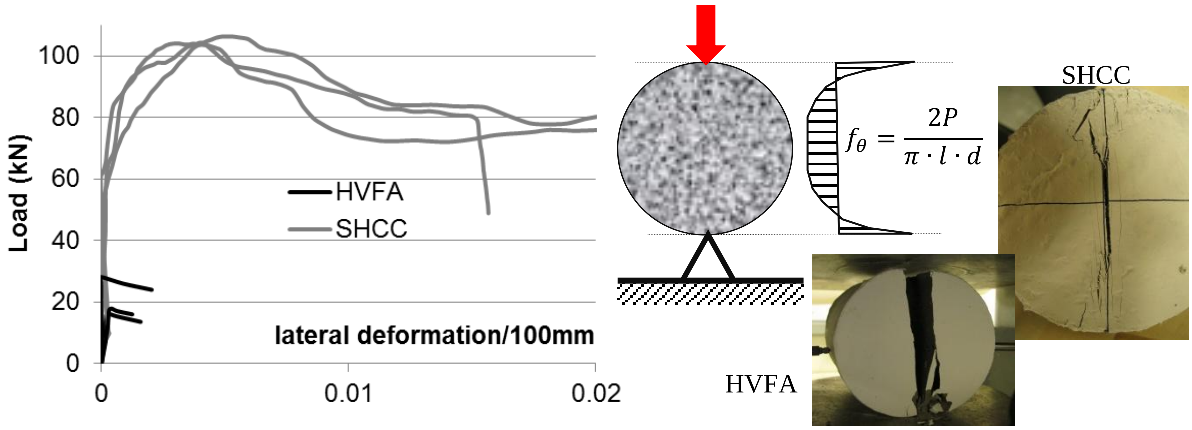

Fig. 7 Split Cylinder (a) machine load to diameter (100mm) extension (δ) measured perpendicular to the direction of cracks, (b) stress distribution during testing and (c) cracking of SHCC and HVFA mixes

The test results depicted in Fig. 7 reveal the beneficial results of the addition of fibers in the cementitious matrix. Regarding the mode of failure, even though the maximum load is concentrated at one plane of the specimen, in the case of the SHCC mix, multiple cracks appear in a wider range on the horizontal diameter of the cylinder of approximately 20mm (the diameter of the specimen is 100mm). This allows the specimen to develop some strain hardening characteristics in comparison to the mix without any fibers that underwent sudden failure past the first cracking strength. Also the fibers seem to increase the first cracking stress in this case as the cracking strength of the HVFA is 1.5MPa while the cracking stress of the SHCC is 4.27MPa.

5.4 Four point bending of beams with and without reinforcement

The advantage of a four-point bending setup in comparison to the three point bending test is that the middle third of the beam develops pure flexure with no simultaneous action of shear. This enables an easy analysis of the state of stress in the middle region and thus, dependable estimates of the tensile stresses. This is more representative of the actual stress capacity as for brittle materials the flaws that could be located at any point and not directly under the central load, are related to crack initiation and tensile strength of the composite [34]. The Load-Deflection diagrams obtained from the four point bending tests (Fig. 8) shows the increase in fracture energy due to the addition of fibers. Yield and ultimate moments at the load application points are calculated from the applied total loads P according with $M_{4pb}=P\cdot a/2$, where a=100mm. The mix without the fibers (HVFA) collapses suddenly past the yield load as the crack rapidly penetrates through the height of the cross section. In this type of test, collapse could occur at any point within the constant moment region where moments attain their maximum value, at some weak cross section, due to internal flaws and microcracking. The properties obtained through the 4-point test for this type of mix differ from the ones obtained from a normal concrete mix of the same compressive strength, owing to the absence of coarse aggregates that would give higher stiffness, and due to the denser microstructure obtained via the use of FA. In the case of the fiber reinforced composite (SHCC) multiple cracking is observed after the first crack, as if the section had been reinforced. The cracking extends outside the constant moment region indicating the strain hardening behavior of the material. The "yield" moment which corresponds to first cracking is used to determine the flexural cracking strength of the composites as it marks the end of the elastic branch. At the extreme tension fiber flexural stress is estimated from: $f_{t,fl}=M/(bh^2/6)$. The load reached by the HVFA mix is 11.1 kN ($M_y=M_u$=0.65kNm) while the yield load for SHCC is 24.37kN (M_y=1.22kNm) and ultimate total load is almost double, at 40.25kN (M_u=2.01kNm). Estimation of the flexural stress from the flexural moment is valid only for the linear part of behavior where the neutral axis is at specimen's mid-height and the stress distribution may be assumed linear to the maximum (yield) strength at the top and bottom surfaces; thus calculation is exact up to yielding (the term corresponds to the end of the ascending branch of the load-displacement response). After yielding, for the SHCC mix fibers bridge the full depth of the tension region of the cross section up till the maximum stress, so the full cross section is participating in the transfer of load. In this context, the equation is no longer exact, but it is used to convert the load to a nominal stress value of the various specimens for comparison purposes.

The addition of flexural reinforcement (2Φ8-beam 4PBR) increases the flexural capacity of the beam and also the shear capacity of the member, as dowel action of the flexural reinforcement contributes to the shear capacity of beams. The failure observed in the beam under consideration was abrupt, with sudden load drop at a machine load just over 80kN. Strain was concentrated at one of the shear cracks that had developed in the shear span, with an inclination of 60^{o} as per the longitudinal axis of the beam. The flexural cracks that developed within the constant moment region of the beam as compared to those of the beam without the flexural reinforcement are sparser making the crack distance of the R/beam wider. The shear failure of this beam prevails the flexural failure due to the reinforcement and the shear span ratio combination. When shear reinforcement is added (stirrups Φ6/50- beam 4PBRS) then the behavior of the beam becomes more ductile, without any sudden load drop even in great deformation levels (δ=10mm, θ=10/100=10%). Also the number of cracks on the beam increases both inside and outside the shear span. Also the initiation of cracks is observed in the compressive zone, under the point loads, but due to the fibers of the composite, no spalling or sudden failure of the extreme layer under compression is observed. Fibers in the matrix work synergistically to the shear reinforcement to prevail brittle failure of any kind. The beams achieves its flexural strength (100MPa) and after the yielding of the flexural reinforcement, it exhibits drift ductility in the order of μ_{θ}=10, much greater than the ductility required by the EC8 for the High Ductility Class.

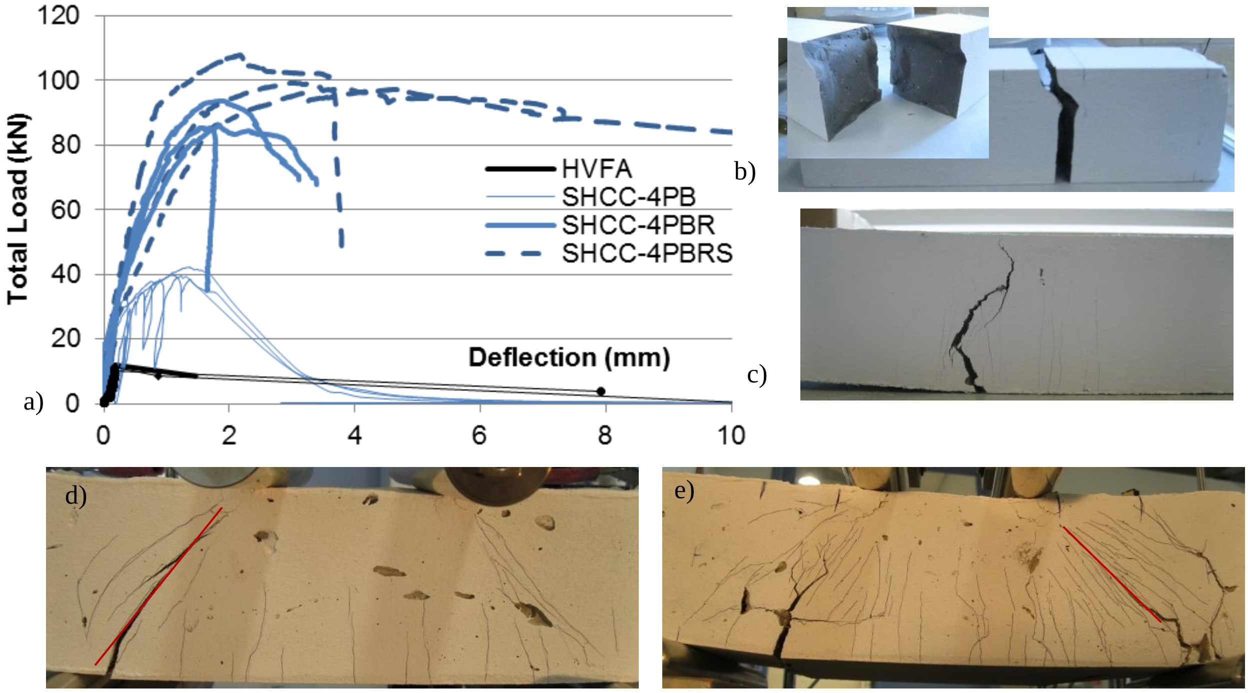

Fig. 8 (a) 4PB tests Total Load-load point deflection diagrams and crack distribution in (b) HVFA, (c) SHCC-4PB, (d) SHCC-4PBR with longitudinal reinforcement, (e) SHCC-4PBRS with longitudinal and transverse reinforcement

Moment yield capacity of a beam with flexural reinforcement is estimated for normal concrete from $M_y=0.85\cdot d\cdot A_{sy}\cdot f_y=0.85\cdot 80\cdot 2\cdot(\pi\cdot 8^2/4)\cdot 500=3.42$kNm. In terms of force applied on a four point bending test with a shear span of 100mm, the total machine load would be $F=2V=2\cdot M/a=2\cdot 3.42/100=68400$N. In the experiments with the strain hardening material in the case of the cementitious matrix the specimens reached a load of 90kN and displayed sudden shear failure. When the same specimen was reinforced with stirrups then the failure became more ductile reaching higher loads up to 100kN - around 40% greater than those expected if normal concrete had been used (68.4kN). This increase in bearing capacity is due to the positive action of the cementitious composite that contributes with the fibers bridging the cracks and transferring load. The difference between the reinforced beam's capacity (100kN) and the yield capacity of the beam without any reinforcement (30kN) is close to the additional contribution of the steel reinforcement (68.4kN). Further analysis of the combined SHCC material with the use of flexural reinforcement is needed towards extracting closed form solutions interpreting their behavior.

5.5 Push off tests

The machine load versus the deformations of the push-off specimen, are depicted in the diagrams of Figure 9 (a). The diagram of the crack opening (Δ_{crack}) for the specimen with stirrups and no fibers (HVFA-S) shows a near to zero lateral expansion up to the maximum load. At maximum load the crack is created and after that, deformation accounts for the crack opening width. The small lateral expansion that develops prior to the maximum load is attributed to elastic deformations. In the beginning of the descending branch the load capacity diminishes from maximum linearly to the crack widening, manifesting the loss of concrete contribution to the shear resistance. The remaining strength that continues to be constant, for greater deformations, is the contribution of the steel reinforcement to the shear capacity. The vertical deformation (Δ_{vert}) of the shear plane (between the crack faces) is in good agreement with the upper (Δ_1) and lower (Δ_2) recess deformations. Here the slope of the ascending branch shows that shear deformation increases shear resistance prior to crack localization, with deformations of the shear plane up to 2mm (length of shear plane is 200mm). After crack is formed, shear capacity diminishes down to the contribution of the steel reinforcement crossing the shear plane.

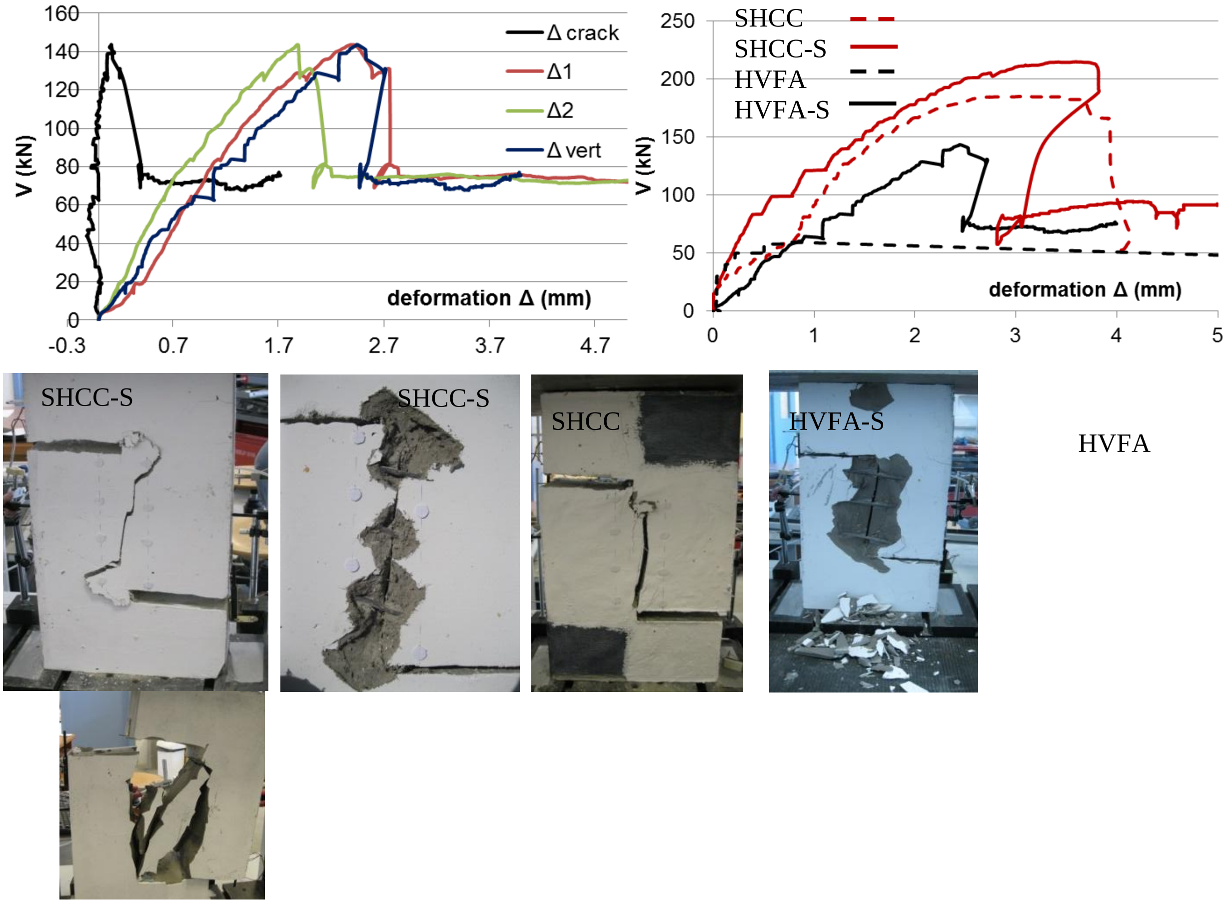

Figure 9: a) Push-off tests Loat-Deformation curves for specimen HVFA-S-1 (with stirrups and no fibers), b) Push-off Load versus vertical deformation for different specimens and c) Push-off crack patterns for all specimens

In Figure 9 (b) the diagrams of shear stress versus normalized crack opening of all push off tests are displayed. The beam with the HVFA mix and without steel reinforcement showed abrupt failure at a load of 60kN. After the peak load that was accompanied by a strong noise the specimen was split in two pieces. Average shear stress attained by these specimens was in the order of 2.5MPa as the fraction of the total applied load to the cross section area under shear. The addition of steel reinforcement (6 bars of 14mm diameter) to the plain mix increases the shear capacity in the order of 140MPa, while the addition of fibers only of 2% by volume increases the shear capacity to 180MPa, triple of that of the plain mix. Also the addition of fibers increases the shear deformation on the vertical axis of symmetry of the specimen, and while the plain mix breaks at a shear deformation of γ=0.5/200=0.25%, the mix with the fibers reaches a deformation of 3.5/200=1.75%. Shear stress seems to increase in the specimens with the fiber reinforced mixes, even though compressive strength of the

SHCC mix is lower than that of the plain mix. This implies that shear strength is related mainly with the tensile stress-strain relationship of the mixes and not with the compressive strength. Stiffness of the specimens is greater in the case of the samples with stirrups, manifesting that steel reinforcement plays an important role in resisting shear even prior to crack initiation. In the case of the SHCC mix without the steel stirrups, cracking initiates at shear stresses close to 1/3 of the maximum shear stress of the samples and past that point stresses are transferred across the crack through the fibers, thereby developing a type of tension stiffening. At ultimate load of the plain SHCC fibers start to rupture and the specimen collapses. All samples containing steel reinforcement after the ultimate load, exhibited a load drop down to an average shear stress of 4MPa, where only stirrups continue to resist shear, and while this value remained constant in the case of the mix without the fibers, there was an increase in resistance in the case of the fiber reinforced matrix, relating bending resistance of the stirrups to the tensile characteristics of the surrounding matrix.

Failure modes of all tested specimens are depicted in Figure 9 (c). The mix without the fibers with steel reinforcement after the shear plane cracked started to delaminate rapidly with the composite cover spalling. Spalling reached half of the width of the specimen (125mm) and deformation of the steel reinforcement was visible at all the 125mm distance. In the case of the fiber reinforced mix without stirrups multiple cracking was witnessed prior to crack localization and failure of the sample. The cracks formed in an inclined to the shear plane angle, with evidence of compression zones at the edges of the shear plane. Failure of the fibers was mixed between rupture and pull-out. The width of the zone where cracks were formed was approximately 4cm but in no case was the composite laterally delaminating. The same type of crack development was evident in the fiber reinforced matrix with stirrups crossing the shear plane. In these specimens though, the inclination of the cracks was greater than the inclination developed at the specimens without the steel reinforcement. Small dislocation of the cracks was developed at the places where the steel stirrups were crossing the cracks. The width of the zone at which cracks were formed was in the order of 6cm, without spalling of the fiber cementitious matrix. The tests in this case were terminated at the point where shear deformation was no longer possible due to the geometry of the sample.

6. Conclusions

Sustainability is a combination of the structural design by increasing the life time of structures and the material design in order to decrease the exploitation of resources and simultaneously assist in achieving the previous goal. Shorter life time of structures is more costly and resource intensive also if one accounts for the greater maintenance costs required. In this research it was shown that the combined effect of the use of high volume fly ash composites and the use of short discontinuous fibers results in materials that exhibit enormous ductility in tension, compression, shear and flexure if compared to normal concrete. This greener material that uses less resources by the exploitation of the great mass of waste materials such as fly ash can improve the durability of structures and its resistance to extreme events that would place excessively large deformation demands on the structure, well beyond the levels implied by the design intensities of the most extreme accidental loads considered by current codes. The aim of this paper was to research the mechanical performance of these cementitious composites that exhibit strain hardening, improved sustainability, high fracture toughness and low resource abuse. Thorough research will enable their adoption by new Codes, enable their spread and development and will give multiple advantages in the field of construction, widening the area of capabilities for innovative cement-based products. It will also enable the development of effective rehabilitation solutions to durability problems encountered in existing structures due to adverse environmental conditions. From the tests it was seen that in cases where cracking behavior was marked by formation of a large network of fine cracks, a superior overall material toughness was obtained. These findings suggest that a whole new generation of Cement based materials is possible, where tensile strength and strain capacities are so high that they provide a totally different context for formulation of concrete mechanics and consequent reinforcement detailing. Additionally the improved performance can lead to more slender member dimensions, reduced amounts of steel reinforcement particularly for shear and confinement, easing construction effort and energy requirements.

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