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High Strength Self Compacting Concrete Incorporating Crumb Rubber Fibre Exposed to Elevated Temperatures

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Abstract--- This paper discusses the review of researches concerning the possibility of utilising crumb rubber in high strength self- compacting concrete (HSSCC). It has been used as replacement for coarse and fine aggregates at various percentage replacement levels. It will also discuss the possibility of utilizing its fibre as an alternative in high strength self- compacting concrete due to the fact that they have similar characteristics. However, the major problem associated with self-compacting concrete is explosive spalling. When crumb rubber from scrap pneumatic tyre is used as a replacement for aggregates in concretes, the major problem encountered is decrease in mechanical properties even though it has the advantage of sound adsorption and damping effect. The decrease in the quality of mechanical properties is usually remedied by the application of supplementary cementing materials such as fly ash, ground granulated blast furnace slag, silica fumes and other pozzolans. The spalling phenomenon has been discussed and efforts made to overcome it. The importance of supplementary cementing materials in trying to overcome this phenomenon has also been discussed.

***Keywords:** self-compacting concrete, crumb rubber, Metakaolin and superplasticiser*

I. INTRODUCTION

Researchers agree that compressive and tensile strengths decrease when rubber aggregates are added in self-compacting concrete (SCC) both in the coarse and fine forms [1]. Even though rubberized concrete usually portrays a tougher reaction under loading than ordinary Portland cement concrete exhibiting greater strain and post fracture toughness [2]. Mineral fillers like silica fumes, fly ash and ground granulated blast furnace slag when used in SCC generate a good and compact paste. In addition, when admixtures are used, greater compressive strength is generally achieved. Durability characteristics can be achieved despite leading to a brittle failure mode. Regarding fresh properties, SCCs should be able to flow through and around formwork in line with relevant guidelines. The inclusion of a rubber phase causes reduction in the workability as typified by the slump flow and J-ring tests [3]. Since rubber aggregates have lesser weight than normal aggregates, they cause reduction in the concrete`s ability to flow under its own weight. It has been reported that sharp and rough edges of rubber particles tend to increase internal friction and consequently decrease slump Hesami, Salehi Hikouei, & Emadi, (2016). It has been found out that after exposure to elevated temperatures, rubber aggregates causes reduction in residual compressive and tensile strengths due to the fact that rubber decomposes between 200 and 300^{o}C thereby creating voids Gupta, Siddique, Sharma, & Chaudhary, (2017). When more than 10% rubber content replacement is exposed to 750^{o}C for 2hours, compressive tests could not be conducted on specimens due to the massive deterioration [5]. Tensile strength decrease with the rubber content was found to be less than that for compressive strength. Similarly, the flexural strength also decreases with the rise in rubber content similar to that for compressive strength. However, they observed that the initial rate of decrease in strength was higher than the one for compressive strength. This is because of the fragile bond between the rubber particles and the cement paste [6].

Spalling is generally due to the effect of differences in thermal stresses and excess pore pressure generated beneath the surface of the concrete that is exposed. Explosive spalling could and may lead to a decrease in cross-sectional areas of structural elements that may lead to loss of thermal protection for steel reinforcement. Fibers have been used with the purpose of trying to improve the mechanical properties of concrete for several years however, its practical application in the field of structural engineering still relies on the provisions of a technical report. A large number of different fiber types have been used as reinforcement in concrete with the sole aim of increasing the strength of the composite materials. For this purpose, steel fiber is usually the more preferred option because of its high modulus of elasticity, which enhances post-peak load carrying capacity of the concrete. However, using polypropylene fibres became an interesting option especially when post cracking residual strength is not of major concern. [7]. Self-compacting concrete have been researched upon over the past two decades. High Strength Self-Compacting Concrete has the benefit of having better mechanical properties than conventional vibrated concrete. This include higher compressive strength, greater tensile strength and stiffness. It is becoming more preferred in structural applications especially where greater durability is more desirable [8] . Some researchers agree that using certain amount of recyclable waste materials like plastic,

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steel and polymers in concrete mixes is desirable due to its economic and environmental advantages [9]. Therefore, there is the need to find alternative ways of mitigating or eradicating this explosive spalling phenomenon that is particularly more associated with self-compacting concretes. Spalling can be defined as the peeling up and breaking away of layers from concrete when exposed to elevated temperatures. It also influences the fire performance behaviour of concrete structural members after being exposed to elevated temperatures [10].

Fires in buildings have always been a threat to life and property. This threat is further aggravated due to the fact that larger number of people live and work in bigger buildings all over the world. Fire hazards are basically unwanted fire accidents that sometimes occur even in the developed economies due to earthquakes and other unforeseen circumstances.

Recently, studies show that fibres can be used to improve residual properties of concretes especially after exposure to high temperatures. Polypropylene has been used in reducing explosive spalling and thereby enhancing strength. It melts between 160-170^{o}C hereby causing pore pressure to develop. This in turn lowers the internal vapor pressure and thereby reducing spalling [11]. [12] investigated the influence of different type of fibres (steel and polypropylene (micro and macro) on the buildup of pore pressure on fibre reinforced high strength self-compacting concrete (FRHSSCC). Their findings indicated that fibre addition prolongs the buildup of pore pressure and that the combination of steel and polypropylene (micro and macro) fibres even help mitigate the spalling behavior better. Similarly, Crumb rubber fibre has been used to mitigate spalling in self-compacting concrete [13] . This is because Crumb rubber has similar characteristics with Polypropylene in that it melts between (200-300 ^{o}C) [13] .

A lot of researchers suggested several approaches in order to remedy the cause of reduction in mechanical properties of concrete caused by introducing rubber aggregates. One of such methods is by using Supplementary Cementing Materials (SCMs), [1] . The optimum Crumb Rubber percentage replacement content for aggregates is 25%. Beyond this percentage concrete begin to lose strength rapidly, for supplementary cementing materials (SCM`s), the optimum percentage is between 20 and 25 % cement replacement. However, investigation into residual behaviour of High Strength Self Compacting Concrete after exposure to elevated temperatures is still being explored. Similarly, the optimum Crumb rubber fibre replacement is still being investigated.

Self-compacting concrete is a type of concrete that flows and spread into the form without the need for mechanical vibration. It can also be described as a modified form of high performance concrete that was developed to solve the durability shortcomings which may likely take place as a result of insufficient compaction in conventional concrete (Najim & Hall, 2010) . It is a non-segregating concrete that is normally placed by virtue of its own weight. Its major importance is attributed to the fact that it maintains all of concrete's durability and characteristics of meeting expected performance requirement. Under certain scenarios, the addition of super-plasticizers to the mix design may be necessary in order to reduce or prevent bleeding in addition to segregation. Self-compacting/consolidating concrete (SCC) class of concrete is ideal for application for highly congested reinforcement members with good workability. With more advancement in concrete technology in producing SCC, its use is becoming more widespread. However, the issue of risk could arise when a structural member made from the SCC class is exposed to fire[8]. Bearing capacity loss may be represented by residual concrete strength. A lot of researches studied the residual behaviour of normal strength concrete (NSC). However, there is no sufficient information about the residual strength of HSSCC incorporating crumb rubber and hybridized fibers after exposure to elevated temperatures.

Over 1.5 billion tires are produced annually across the globe. This is a cause for concern especially pertaining to environmental pollution. Previous studies show that crumb rubber and fibre from scrap tire is produced at a cheaper rate and provides material for various purposes for example sport surfaces used for athletics. Adding it to concrete provides a good alternative for waste tire application, because it enhances weight reduction in concrete giving rise to less dead loads thereby placing less stress on building foundations and enhancing the efficiency of the structure. However, the addition of crumb rubber aggregates to concrete systematically causes reduction in the tensile and compressive strengths despite exhibiting a higher level of strain at failure as indicated in previous research [15] .

Crumb rubber from waste tires has been used to replace aggregates in concrete either in part or in full or to modify bituminous composites. Accumulation of waste rubber tires especially from light vehicles poses environmental risks in the long term. This is because polymers are difficult to decompose. When stockpiled, tires can trap water and this could breed insects especially mosquitoes which could result in malaria or dengue fever outbreak etc. Specifically, when disposed for landfill, chemical leeching and landfill instability could arise. This problem is being tackled globally. The United States recycled 3.824 million tonnes of waste rubber tire in 2013 [16] . Using aggregates made of recycled crumb rubber (CR) as an alternative for the more popular traditional aggregates in concrete has been investigated over the past decade. This is due to the fact that there is a growing clamour to seek useful applications for crumb rubber waste [15]). Crumb Rubber aggregates comprises of 45% polymer, 15% organic materials and 40% carbon black by weight [17].

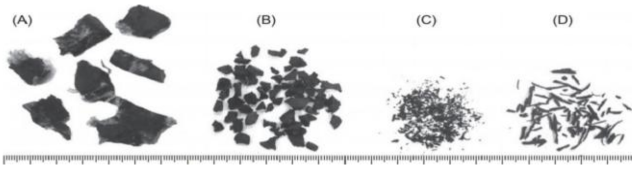


Figure1:Rubber Aggregates Classification: (A) Shredded Rubber, (B) Crumb Rubber, (C) Granular and (D) Fiber Source: [17].

II. Properties of Fresh SCC

[18], stated that for the SCC class concrete, workability is the ability for it to flow unaided under its own weight, aerate and consolidate itself without the need for vibration and without segregation. A concrete mix will only be classified as self-consolidating if all these three characteristic requirements are met.

i. Filling ability: Ability to be able to fill and navigate to all the corners of a formwork
ii. under its own weight.
iii. Passing ability: Ability to go past obstacles under its self-weight with little or no hindrance. Congested reinforcement is an example of Obstacle that could be met
iv. Segregation resistance: To be able to maintain a homogeneous composition of the concrete mix despite movement during transportation and while placing.

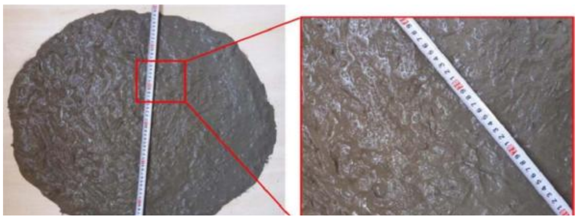


Figure 2:Typical Slump measurement-T_{500} Source: [9]

Table 1: List of test methods for workability of SCC (EFNARC, 2002)

S/NO	Method	Properties
1	Slump flow by Abrams Cone	Filling ability
2	T500cm	Filling ability
3	J-ring	Passing ability
5	V-funnel	Filling ability
6	Time increase, V-funnel at T5minutes	Segregation resistance
7	L-box	Passing ability
8	U-box	Passing ability
9	Fill box	Passing ability
10	GTM screen stability test	Segregation resistance
11	Orimet	Filling ability

2.1 Influence of Crumb Rubber on Vibrated Concrete and SCC Properties

2.1.1 Fresh Properties

A lot of researchers suggested several approaches in imperative to mitigating the reduction in mechanical properties of concrete caused by introducing rubber aggregates. One method is by using supplementary cementing materials SCMs. [19], investigated the outcome of using silica fume on the mechanical properties of vibrated reinforced concrete mixtures incorporating crumb rubber tire chips with as much as 50% replacement by volume. They observed that adding silica fume could reduce strength loss, allowing VRC mixtures containing 15% rubber content to be produced having compressive strength of 40 MPa. [20], stated that the addition of 15% silica fume to vibrated reinforced concrete can cause the 28-day compressive strength increase and also improves the interfacial transition zone (ITZ) bonding, which causes reduction in concrete strength as a result of splitting tensile strength (STS) up to 32.9% and 32.2%, respectively in comparison to mixtures without silica fume. Results of similar nature were obtained by [21] confirming the advantages of silica inclusion in waste rubber concrete. Some researchers also suggested that mechanical properties of rubberized concrete could be enhanced chemically pre-treating the rubber particles surface, which improves the bond between cement paste and rubber. Preceding studies suggested diverse treatments, like the usage of polyvinyl alcohol, sodium hydroxide and sulfur compounds [22]; [23]. However, even after treatment, researchers did not observe major significant enhancement in the compressive and tensile strength of rubberized concrete.

2.1.2 Usefulness of Rubber in Concrete

Although the mechanical properties of concrete decreased by inclusion of rubber, significant research has shown that recycling crumb rubber as aggregate replacement can be a promising technique to develop concrete having improved dynamic properties and higher ductility. [24], reported that rubber aggregates enhanced the strain capacity of concrete to a great extent, leading to the crack mouth opening displacement decrease. Additionally, rubber content increase exhibited a significant development in the flexural toughness, that had a direct influence on improving the concrete's ductility energy absorption and ductility. [14], equally established that rubberized concrete`s damping coefficient at 15% crumb rubber content improved by 230% in comparison to concrete with no CR. [2], stated that when adequate rubber content is used, the ductility and fracture energy of the concrete could be enhanced. Nevertheless, concrete ductility and its capacity for absorbing higher energy could be affected negatively when rubber content is increased significantly.

[24], showed how concrete`s fatigue strength can be improved when scrap rubber is added to the mixture. [25], also corroborated this by stating that concrete`s fatigue life became enhanced with percentage rubber content increase thereby attaining optimal strength as rubber content reaches 20% replacement level with regards to fine aggregate volume. [26] examined the outcome of utilising up to 20% waste rubber for partial replacement of both cement and sand on the impact resistance of vibrated reinforced concrete beams. The researchers observed that in the case of impact energy with respect to first crack and failure crack, they continuously increase as sand replacement with fine CR increases, while for rubber powder, it was shown to be an optimal replacement for cement. [27] also reported that replacing the fine aggregate with waste rubber fibre (up to 25% by volume) greatly improved the impact absorption

energy of VRC. [28] observed similar results in VRC beams, in which the CR was used as a replacement for fine aggregate in percentages ranging from 0% to 100% in 25% increment (by volume). This investigation indicated that 50% crumb rubber replacement level could achieve the maximum impact energy, while the beams with 75% crumb rubber exhibited impact energy mostly equal to that of the control mixture (CR = 0%).

Researchers also examined rubberized concrete`s performance in terms of durability. It was discovered that adding waste rubber to concrete enhances resistance to abrasion, freezing-thawing action, and acid attack [21]. Such improvements may extend the possibility for the application of rubberized concrete in temperate environments and for offshore structures. Reutilization of CR in concrete mixtures can also play an important role in enhancing the sound absorbance of concrete. Such enhancement provides a promising potential for rubberized concrete to be used in applications, such as eliminating sound transmission through walls, floors, and ceilings. J. Xie et al., (2018) investigated the sound absorbance of concrete panels containing CR as a fine aggregate replacement. In the study, VRC mixtures were tested with two volumetric replacement levels of CR (7.5% and 15%) and with different grades following freezing and heating. The researchers stated that the developed mixtures showed a good performance in terms of sound absorbance, with no significant effects for freezing and heating. Another investigation by [29] also confirmed the beneficial effect of rubber on improving the sound absorption capacity of concrete, recommending such type of concrete to be used as a sound absorbing barrier in areas with high noise levels.

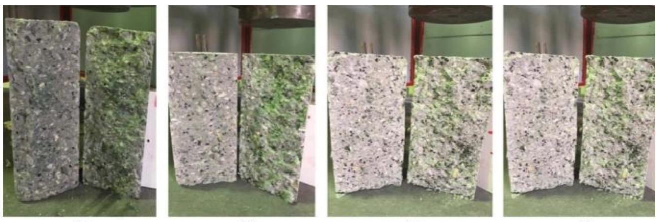
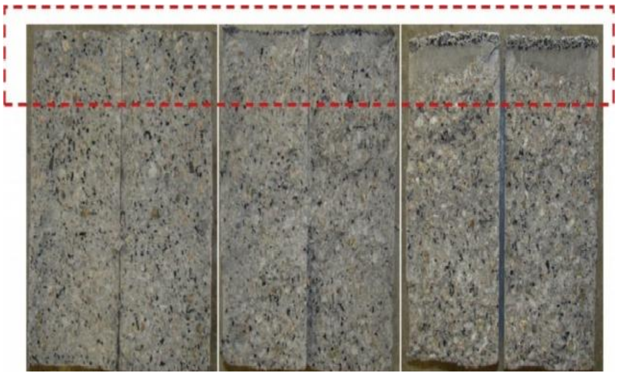


Figure 4: Showing SCC Containing 3-5 mm CR aggregates (a-10%, b -20%, c-30% and d -40%) Source : ([16]



(a) (b) (c)

Figure 5: Rubber particles stability: (a) no segregation (NS), (b) moderate segregation (MS), (c) heavy segregation (HS) Source: [1]

2.2 Properties Influencing Fire Resistance

The behaviour of reinforced concrete (RC) elements is basically determined by the attributes of its constituent materials which are concrete and reinforcing steel. These characteristics consists of (1) thermal properties, (2) mechanical properties, (3) deformation properties, (4) material specific characteristics for example spalling in concrete. Thermal properties govern the extent of heat to be transferred to a structural member, while mechanical properties of the individual constituent materials regulate the extent of stiffness deterioration and strength loss in member elements. Strains and deformations are determined by the deformation properties in addition to the mechanical properties of the structural member. The influence of weight, strength, and fibers on concrete properties at high temperatures is emphasized. Recently, concrete having a compressive strength in the range of 50 to 120 MPa is denoted as high strength concrete (HSC). Once compressive strength is in excess of 120 MPa, it is considered as ultrahigh performance concrete (UHP). Concrete strength decreases with increase in temperature and the degree of strength reduction is greatly determined by the compressive strength of concrete

2.3 Properties of Concrete at elevated temperatures

2.3.1 Thermal properties of concrete when subjected to elevated temperatures

The thermal properties that define temperature dependent properties in concrete elements include thermal conductivity, specific heat (or heat capacity), and mass loss. They are influenced to a large extent by the type of aggregate, moisture content, and the concrete mix composition. Several test programs exist for depicting thermal properties of concrete at elevated temperatures.

2.3.2 Thermal conductivity

Thermal conductivity of concrete at room temperature lies within the range of 1.4 and 3.6 W/m^{o}K and this varies with temperature. Thermal conductivity is generally dependent on concrete mix properties especially the concrete .

2.3.3. Specific heat for concrete, its specific heat at room temperature ranges between 840 J/kg.K and 1800 J/kg.K for different aggregate types. It is often expressed in form of thermal capacity that is the product of specific heat and density of concrete. It is especially sensitive to several chemical and physical changes which occur within concrete at elevated temperatures. This involves the vaporisation of free water at about 100^{o}C, the dissociation of $Ca(OH)_2$ into CaO and H_20 within the range of 400— 500^{o}C, and the quartz transformation of some aggregates above 600^{o}C. Specific heat largely depends on moisture content and increases significantly with higher water to cement ratio.

A lot of pioneer researchers mainly concentrated on compressive strength and/or elastic modulus instead of the complete stress - strain relationship. When concrete is exposed to fire, its behaviour is generally determined by its

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mix composition and complex interactions while heating progresses. Failure modes of concrete exposed to fire changes according to the severity of fire, types of structure and loading system. Additionally, this failure could happen for other reasons like reduction of bending, loss of shear, tensile strength, loss of compressive strength or torsional strength etcetera Mohamed Bikhiet, El-Shafey, & El-Hashimy, (2014) . Reduction in residual compressive and tensile strengths have been observed in rubberized concrete. This is due to the fact that the rubber decomposes between (200 - 300°C) thereby creating voids in the concrete [16] .

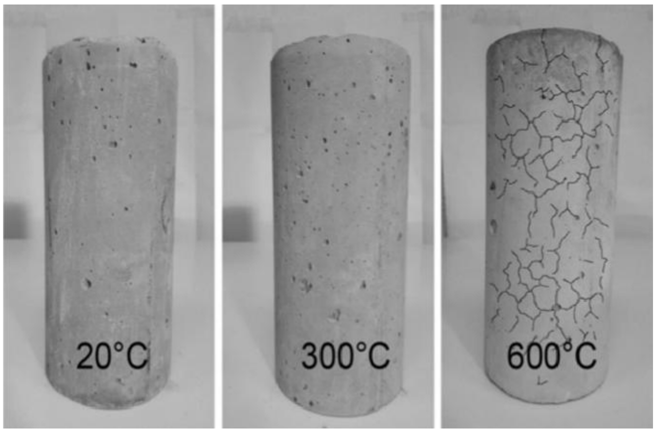

Figure 6:View of SCHSC samples after thermal treatments Source: [31]

NC-RO RC-RO RC-R4 RC-R8 RC-R12 RC-R16

(a) Failure mode of mixes exposed to 25°C

NC-RO RC-RO RC-R4 RC-R8 RC-R 12 RC-R16

Failure mode of mixes exposed to 200°C

Failure mode of mixes exposed to 400°C

NC-RO RC-RO RC-R4 RC-R8 RC-R 12 RC-R 16

Failure mode of mixes exposed to 600°C

Figures 7 (a-d) Failure modes of concrete mixes exposed to elevated temperatures Source: [2] .

2.3.4 Properties of High Strength SCC in Fire

It was concluded in earlier research into rubberized concrete that when rubber content is increased in concrete it causes the mechanical strength properties to decrease [17] . The effect of replacing fine aggregates with crumb rubber was analysed and adduced that up to 25% fine aggregate replacement can still provide adequate strength. The decrease in density at 25% replacement is 8% while the improved ductile characteristics were portrayed when compared to normal concrete favoured in applications like highway barriers and shock resisting elements [32] . Further replacement beyond 25% resulted in a drastic reduction in strength and exhibited unpredictable stress-strain behaviour. [26] stated that the fragile bond that exists between rubber aggregates and the surrounding cement matrix develop into a weak interfacial transition zone (ITZ) which makes the rubber particles to behave in a void like manner hence affecting its compressive strength. Additionally, in a situation where rubber particles contract more than the surrounding cement matrix during loading, cracks will be instigated within the fragile layer of ITZ thereby quickening the failure mechanism of rubberized concrete.

2.4 SCC Mixes

Research on Self Compacting Concrete (SCC) was started by Okamura in Japan in 1986. SCC is a non-segregating and highly flowable concrete that occupies the formwork and surrounding reinforcement without requiring any vibration [17].This achievement is made by the addition of large amounts of fine active pozzolanic fillers to the mix (for example silica fume, blast furnace slag, fly ash) in conjunction with chemical admixtures like a super-plasticiser in order to enhance the flow properties and a viscosity-modifying agent to aid segregation resistance [16] . The major advantage is that neither vibration nor skilled labour is required thereby allowing for effective placement in order to achieve a consistent product with the ability for casting more complex shapes. The major advantage SCC class of concrete has over conventional concrete is its capacity to flow through and around reinforcement in congested areas where vibrating techniques cannot be utilized [16] .

2.4.1Mix Proportions

A 450 kg/m^3 control mixture binder content with a 0.45 water to binder ratio was maintained by [17] throughout his experimental study. The binder content in the control mixes comprises of 40% cement, 32.5% Fly ash, 22.5% Ground Granulated Blast Furnace Slag (GGBFS), and 7.5% Silica

Fumes. He designed three separate sets of self-compacting rubberized concrete (SCRC) mixtures. The first two sets contained fine natural aggregates (Natural crushed 4 mm) replaced with 2 mm and 5 mm sized crumb rubber (CR). The third had coarse natural aggregates (Natural crushed 10 mm) replaced with 10 mm sized CR. The three different crumb rubber sizes were substituted incrementally in percentage ratios of 10%, 20%, 30%, and 40% of the total respective sized aggregates.

[31], prepared concrete mixture proportions whose target 28 days cylindrical compressive strength was 80 MPa. They initially designed mixture for the SCHSC, the same cement matrix was utilised for SCHSC and SCFRHSC. Granitic crushed and siliceous river sand were used as fine aggregates having fineness moduli of FM = 1.77 and FM = 3.52, respectively. The coarse aggregates consist of granitic crushed stone having FM — 5.69. The combination of fine and coarse aggregates was also utilised and the distribution is: 18% natural sand, 32% crushed sand and 50% coarse aggregates. The fineness modulus resulting from the combination of these aggregates was FM = 4.29, with the particle size distribution achieved through sieve analysis. A maximum nominal coarse aggregate size Umax of (¼)inch or 9.50 mm was used. High strength cement -similar to Type Ill, ASTM- was employed and mixed with mineral and chemical admixtures

Table 2: Concrete mixes used for SCC Source: [31]

Components	Mass of Constituents (Kg/m^3)	
	SCHSC	SCFHSC
Cement (c)	429.8	425.5
Blast furnace slag	183.9	182.4
Water (w)	214.6	212.8
Fine Aggregates	780.8	774.2
Coarse Aggregates	783.7	777.1
Superplasticizer	3.1	3.1
Steel macro fibres	0.0	60.0
Polypropylene micro Fibers	0.0	0.9
Water/binder ratio	0.35	0.35
Binder = cement + slag contents (b=c+s)	-	-

[33], produced SCC using Ordinary Portland Cement (OPC) in addition to limestone filler (98%). They produced specimen with water/cement (w/c) ratio of 0.41 and 0.48 which they compared with HPC of w/c ratio of 0.33. Their other specimen containing polypropylene fibers (PP) with a length of 12mm and diameter of 18um were later added. Dimension of specimen used was 300 x 300 x 150mm. They subsequently embedded thermo-couple and pore pressure sensors prior to casting.

Other researchers use similar mix designs but with slight variations: Five different mixtures having same cement content (377 kg/m^3) were obtained by gradually reducing the free water content (from 227 to 140 1/m^3) and subsequently raising the super-plasticiser dosage (from 3.7 to 13.0 1/m^3) in order to achieve the required range of slump flow of between 65—80 cm. Various potential SCC mixtures having diverse theological properties can be produced by altering the amount of mixing water and plasticizer dosage. The self-compacting ability depends on the concreting case [14].

Four concrete mixes were prepared by [34] with total powder content of 500 kg/m^3. Coarse aggregate content was pegged at 51% by volume of concrete with fine aggregate at 49% by mortar volume in concrete. The water-powder ratio was varied from 0.38 to 0.42 by weight and air content assumed as 2%. In their research, one control mix (SCCI) was designed with Ordinary Portland cement with the remaining three mixes (SCC2-4) prepared by replacing cement with 30%, 40%, and 50% of Class F fly ash and by replacing 10% of fine aggregate with spent foundry sand.

Table 3: Mix Proportions in kg/m3 Source: [33]

	SCCOIPPFO	SCC02PPFO	HPCPPFO
Portland Cement 152.5	400	400	400
Water	165	192	152
Sand	853	782	650
Aggregate 4-8 mm	300	300	530
8-16 mm	400	340	720
Limestone Powder	200	300	-
Glenium 51 (liter)	3.2	2.7	-
Superplasticizer Rheobuild	-	-	8.45
Total Powder Content	600	700	400
Water cement ratio	0.44	0.48	0.33
Water powder ratio	0.28	0.27	0.33

2.5 Parameters Affecting the Performance of SCC/HSC

Chemical admixtures play a major part in the production of SCC. High range water reducer admixture is a good example (HRWRA), otherwise known as superplasticizer is necessary for development of mixtures with adequate flowability while maintaining a reasonable water-binder (w/b) ratio [35]. The HRWRA provides all cement particles high negative charge which help disperses the particles and reduces friction, thereby improving the workability. Super plasticizer similarly allows SCC to be produced with lower w/b ratio, which helps increase strength and durability of concrete [14] ; [36]

2.6 Effect of Silica Fumes (SFs)

2.6.1. Fresh and Mechanical Properties of Concrete

Utilising silica fumes (SF$_S$) in crumb rubber concrete can effectively compensate for the reduction in splitting tensile strength and flexural strength resulting from the addition of crumb rubber. Additionally, the inclusion of (SF$_S$) can also improve flexural toughness, impact strength, ductility, and limit the crack widths in concrete [9]. For example, [9] investigated the mechanical properties and impact resistance of VC mixtures developed with different water-cement ratios and different SF contents. The researchers reported that using 0.5% and 1% SFs appeared to increase the tensile strength by a range of 9%-20% and 30%-62%, respectively, compared to mixtures with no SFs. Also, the impact resistance showed increases reaching up to 3.5 to 10.2 times and 7.2 to 12.4 times in mixtures with 0.5% and 1% SFs, respectively. J. Xie et al., (2018) also studied the effect of SFs with an aspect ratio of 40 on the impact resistance of VC using two different compressive strengths (30 MPa and 50 MPa).

The results indicated that adding 0.5% (SF$_S$) showed an improvement in the impact resistance of mixtures with 30 MPa reaching up to 3 to 4 times greater than the control mixture, while this increase was 7 to 10 times in mixtures with a strength of 50 MPa. However, the addition of SFs has a significant negative effect on the fresh properties of concrete, especially when SCC is used. Mastali & Dalvand, (2017) showed that increasing SF$_S$ (20 mm length) higher than 0.5% in SCC mixtures with 600 kg/m3 powder content exhibited unacceptable L-box test results (L-box ratio is less than 0.75). [16] also studied the effect of using up to 1.25% SFs (13 mm length) on the properties of lightweight SCC.

The study reported that the addition of SF$_S$ appeared to improve the STS and FS of concrete, while the flowability reduced as the volume of SF$_S$ increased. No data was provided for the passing ability. The same effect of SF$_S$ on the fresh properties of SCC was also noted by other researchers [37] . These improvements in both shear and flexural behavior are attributed to the ability of SFS to transfer stress across the cracked sections by fibres' bridging mechanism, which provides a residual strength to concrete [37] . Moreover, the fibres' stitching action has an effective role in controlling the development of cracks and limiting the crack openings [37].

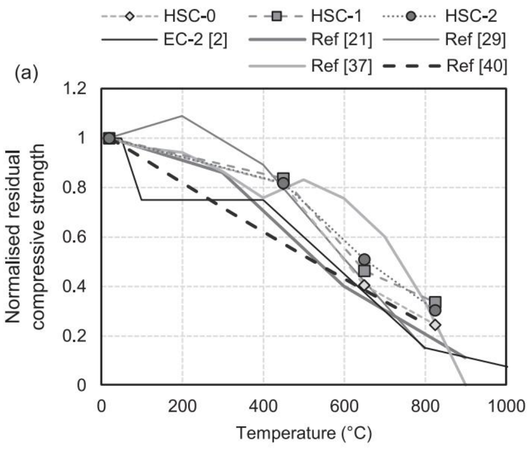

Fig 8a: Effect of Temperature on Residual Compressive Strength, Source: [37].

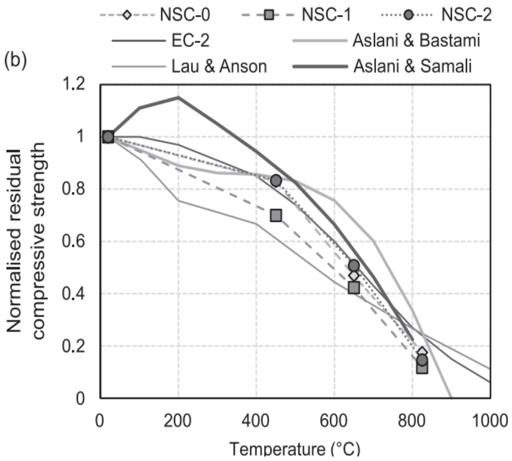

Fig 8b: Effect of Temperature on Residual Compressive Strength, Source: [37].

Conclusion

It has been shown that crumb rubber fibre can be used as a replacement for polypropylene in mitigating the explosive spalling of self-compacting concrete by the use of silica fumes or other supplementary cementing material additives.Crumb Rubber (CR) have been investigated by several researchers over the last two decades and most of them reported that:

a) When rubber content is increased in concrete it causes the mechanical strength properties to decrease.
b) Several researchers reported that reutilising waste rubber as aggregate replacement can be a promising technique to develop concrete with improved dynamic properties and higher ductility.
c) When concrete is exposed to fire, its behaviour is generally determined by its mix composition and complex interactions while heating progresses. The failure modes of concrete exposed to fire changes according to the severity of fire, types of structure and loading system.
d) The effect of replacing fine aggregates with crumb rubber was analysed and it was concluded that up to 25% fine aggregate replacement will still provide good strength.

Reduction in residual compressive and tensile strengths have been observed in rubberized concrete. This is due to the fact that the rubber decomposes between (200 - 300^{o}C) thereby creating voids in the concrete. However, this can be remedied by the use of supplementary cementing materials.

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