Thermo-physical and mechanical analysis of Self-Compacting Rubberised Concrete (SCRC) mix classes

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Abstract

The presented work experimentally investigated the fresh and some hardened properties of Self-Compacting Rubberised Concrete (SCRC). It produced by substituting crumb rubber aggregate by 5% (44 Kg/m^3), 10 %(88 Kg/m^3), and 15% (132Kg/m^3) weight replacement, and as Fine Aggregate (FA), Coarse Aggregate (CA), and a combination (FCA, i.e. 50% FA and 50% CA). The aim was to determine the effects of substitution on the fresh properties, unit weight, apparent porosity, and both dry and saturated thermal conductivity, diffusivity, effusivity, and resistivity in addition to specific heat capacity values. The fresh properties were evaluated in terms of flowability (filling ability), viscosity, passing ability, and static segregation resistance. The initial results indicated that good quality SCRC can be produced containing ~100 kg/m^3 (10%wt CA, FA, and CFA) crumb rubber with a slight increase in SP

dose. Additionally, all SCRC offered significant improvements in thermal insulation for all types of aggregate replacement to a maximum amounting to ~30% to 40% in dry state, and 44% to 46% in wet state, respectively.

Abbreviations

FA = Fine aggregate
CA = Coarse aggregate
CR= Coarse aggregate rubber replacement
FR= Fine aggregate rubber replacement
FCA = Fine and coarse aggregate
FCR= Fine and coarse aggregate rubber replacement
E_d = Dynamic modulus of elasticity (GPa)
f_{cu} = Unconfined compressive strength (MPa)
UPV= Ultrasonic pulse velocity (m/sec.)
SCRCFR= Self compacting concrete with fine aggregate replacement
SCRCCR= Self compacting concrete with Coarse aggregate replacement
SCRCFCR= Self compacting concrete with fine and coarse (0.5 each) aggregate replacement
λ^*= Saturated thermal conductivity (W/m K)
λ= Dry thermal conductivity (W/m K)
Cp= Specific heat capacity (J/kg K)
α= thermal diffusivity (m^2/s)
β= thermal effusivity ($J/s^{0.5}\ m^2K$)
R= Thermal resistivity (m^2/K W)
ρ= density (kg/m^3)

1. Introduction

Self-Compacting Concrete (SCC) can be described as a modified class of high performance concrete; developed to overcome the durability shortcomings that may take place due to insufficient consolidation in conventional concrete [1-3]. It is argued that it presented the most important achievement in terms of concrete technology in recent years [4] thanks to the excellent flowability rate and high segregation resistance and also the ability to be compactable under its own weight without the need for external vibration [5,6]. SCC reduces concrete costs by increasing the productivity rate, decreasing the manpower and reducing noise and the fuel which is used by vibrators. Furthermore, emissions of green-house gases and energy consumption can be mitigated by reducing cement used whilst utilising pozzolanic and cement-replacement materials whether natural or by-product (see Fig.1) [7-9]. In other words, using SCC widely is the easiest way to make the concrete more sustainable by consuming different kinds of recycled and waste aggregate instead of primary resources [3].

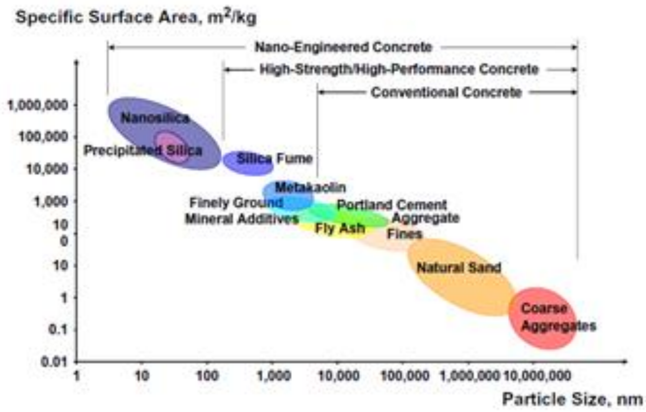

Fig.1: Materials that can be used in SCC (adapted from [10])

The continued growth in world population and the development in living standards have led to considerable increases in global energy consumption. This coupled with predicted global warming phenomena means that one of the routes that can be followed to mitigate energy consumption (through demand-side reduction) is enhancing the thermal insulation of

buildings by using low thermal conductivity construction materials. It is well known that concrete is one of the most consumed materials by the construction industry [11] estimated at around 12 billion tonnes annually [12]. Therefore, reducing its thermal conductivity could improve the operational energy efficiency of buildings and make significant demand-side reductions [13] taking into account that more than 30% of the total global energy consumption is consumed in this sector [14]. Aggregate physical properties are one of the most influential factors affecting concrete thermal insulation [15], thus using low thermal conductivity aggregates coupled with increased air entrainment is a logical way to improve concrete thermal resistance [16]. Re-used, end-of-life vehicle tyres can be processed into crumb rubber particles for use as an aggregate in concrete production and could meet the aims of environmental sustainability, reduced thermal conductivity, and as a lightweight aggregate [17].

The accumulation of significant quantities of scrap tyres has become a vital waste management challenge due to environmental concerns over disposal and combustion alternatives [18]. The tyre production has been raising continually owing to annual car production numbers, for example, in the UK in 2007 almost 46 million tyres were used and this number is growing continuously [19], whereas in the USA this figure is about 275 million scrap tyres per year [20]. Accordingly, scrap tyres have been identified as a sustainable resource for generating quality alternative aggregate.

A small quantity of waste tyres have been utilised in applications such as making barriers to protect offshore structures and marine platforms against impact from waves or ships, and also combustion or co-firing with other fossil fuel (e.g. cement kilns), which has to managed in order to limit air pollution [21]. Many governments around the world, for instance in the EU

since 2006 [22], have forbidden stockpiling or landfill of scrap tyres whilst at the same time encouraging re-use of them as alternative aggregates, e.g. through the combined approach of aggregate extraction levies and landfill taxation [23]. Although a considerable number of studies have been conducted to exploit the use of chipped or crumb rubber aggregates in Plain Rubberised Concrete (PRC), very limited investigations have been conducted to study the possibility of producing Self-Compacting Rubberised Concrete (SCRC) (reviewed by Najim and Hall [24]).

The aim of this study was to investigate the fresh and hardened physical properties, including the thermo-physical properties of both wet and dry state thermal conductivity, diffusivity, effusivity, and thermal resistivity of SCRC produced using different amounts of rubber replacement. Crumb rubber was used to replace sand, gravel, and a combination (50% sand and 50% gravel) at 5%wt, 10%wt, and 15%wt replacement.

2. Materials, Mix design and Preparation

The raw materials used in this study, and their physical properties, are described in a previous study by Najim and Hall [25]. The SCC mix was designed in accordance with the guideline limitations of EFNARC (the **E**uropean **F**ederation of **N**ational **A**ssociations **R**epresenting producers and applicators of specialist building products for **C**oncrete) [7] (see Table 1). 2.5%wt SP and 30%wt PFA, as a proportion of cement mass, were used to achieve a 730mm slump flow and to meet the other SCC requirements (detailed in [25]). All solid ingredients were mixed for three minutes in a rotary mixer, before adding the pre-mixed water and SP and a further three minutes of mixing. Finally, the mixes were left to rest for about two minutes before measuring the fresh state properties. Table 2 shows the mix design

proportions and the compressive strength, which are also detailed in a previous study [25], of all SCRC mixes.

Table 1: Limitations of SCC mixes [7]

Test	Class	Value	Description
Slump-flow	SF1	550-650 mm	Low filling ability
	SF2	660-750 mm	Good filling ability
	SF3	760-850 mm	High filling ability
T_{50}	VS1	≤ 2Sec.	good filling ability and moderate to high flow rate
	VS2	> 2sec. Typically ≤ 5 sec.	
J-ring spread	SF_J1	550-650 mm	Low filling ability
	SF_J 2	660-750 mm	Good filling ability
	SF_J3	760-850 mm	High filling ability
T_{J50}	VS1	≤ 2Sec.	good filling ability and moderate to high flow rate
	VS2	> 2sec. Typically ≤ 6 sec.	
B_J	B_J1	≤ 10 mm	Zero or low risk of blocking
	B_J2	>10 , ≤ 20	Moderate or high risk of blocking
V-funnel	VF1	≤ 8 sec.	good filling ability and moderate to high flow rate
	VF2	>9sec.,≤ 25 sec.	Moderate to low filling ability, low flow rate
Segregation resistance	SI1	≤ 20 %	Adequate resistance to static segregation (settlement)
	SI2	≤ 15%	Good resistance to static segregation (settlement)

Table 2: Mix proportion and compressive strength all tested mixes (*published in [25])

Mixes	W/b ratio	Weight kg/m^3							*f*cu MPa*
		Cement	PFA	SP	Water	Sand	Gravel	Rubber	
SCC	0.37	363	109	9	174	881	881	0	56
SCRCFR5%	0.37	363	109	9	174	837	881	44	37
SCRCFR10%	0.37	363	109	9	174	793	881	88	32
SCRCFR15%	0.37	363	109	9	174	749	881	132	25
SCRCCR5%	0.37	363	109	9	174	881	837	44	44
SCRCCR10%	0.37	363	109	9	174	881	793	88	33
SCRCCR15%	0.37	363	109	9	174	881	749	132	23
SCRCFCR5%	0.37	363	109	9	174	859	859	44	44
SCRCFCR10%	0.37	363	109	9	174	837	837	88	38
SCRCFCR15%	0.37	363	109	9	174	815	815	132	27

3. Test Programme

To evaluate the fresh properties of SCC and all SCRC mixes, the following tests were employed following EFNARC [7] and Shutter *et al* [26]. These particular tests have been suggested elsewhere [26] to provide the best final performance data and for practical convenience:

Flowability (filling ability): described by the slump-flow test under unconfined conditions and used as a 'primer check' to judge whether the fresh concrete consistency is likely to meet the specifications for SCC.

Viscosity: measured indirectly whilst performing the slump-flow test by T_{50} time (defined as the time concrete needs to flow to a pool of diameter 500mm) or by the V-funnel test. Both tests do not measure the viscosity directly but provide an indicator by assessing rate of flow.

Passing ability: measures the ability of concrete to pass through congested reinforcement bars and narrow openings without blocking. It can be measured using the J-ring test which primarily evaluates the passing ability but also the filling ability and flow-rate. From the J-ring test, three results can be evaluated:

- Blocking step (B_J), which indicates the mix blocking probability when passing through reinforcement bars. It is defined as the difference in height Δh between the concrete height in the original J-ring centre (h_o) and concrete height just outside the ring (h_{xn}), measured as the average of four readings, as shown by Eq. 1:

$$B_J = \frac{(h_{x1} + h_{x2} + h_{x3} + h_{x4}) - h_o}{4} \quad (1)$$

- J-ring flow (SF_J) (i.e. spread) indicates the passing ability through reinforcement bars. However, to satisfy the necessary level of passing ability, the value of SF_J must be confirmed by an adequate value of B_J.
- T_{j50} time indicates the flow speed constrained by J-ring reinforcement to reach to a distance of 500mm.

Segregation resistance: is the capability of the fresh mix to conserve the original solid ingredients (aggregate) distribution inside the mixture during transport, placing and compaction. It can describe the quality and homogeneity of in-situ SCC.

Unit weight and unconfined compressive strength were determined in accordance with BS 1881-114:1983[27] and BS 1881-116 [28], respectively, whilst Apparent Porosity (AP) was measured using the total absorption method. The mean average value of three 100mm cubes was calculated to determine all of these properties.

Saturated (λ^*) and oven dry (λ) thermal conductivity were experimentally measured using computer-controlled P.A Hilton B480 heat flow meter apparatus (Fig. 2) with vertical downward heat flow. The calibration constants are used to calculate the thermal conductivity by measuring the heat flowmeter output and mean temperature of the tested specimen, as described elsewhere [29]. The average of two 300x300 mm, and 60-70 mm thickness slab results was recorded.

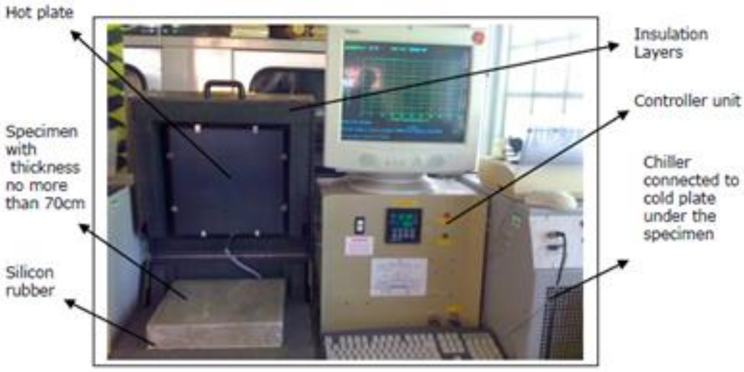

Fig.2: P.A Hilton B480 heat flow meter apparatus

The specific heat capacity of concrete c_p was calculated proportionally as the summation of the heat capacities of all ingredients [30]. It was determined for each ingredient using a Differential Scanning Calorimeter (TA instruments Model Q10 DSC) and the ramp rate method, where the mean of five readings across the range -15°C and 60°C was taken. The specific heat capacity of cement paste, coarse and fine aggregate, and crumb rubber are listed in Table 3.

Table 3: The specific heat capacity (J/kg K)

	Water	Cement paste	Sand	Gravel	Rubber
Cp	4180	1460	689	765	1406

The air content was assumed to have negligible effect on the specific heat capacity of concrete. The concrete dry (c_p) and wet (c_p*) specific heat capacity were calculated based on Eq. 2 and 3[31], respectively.

$$Cp = \frac{1}{W_{total}}[W_{HCP}C_{HCP} + W_{CA}\,C_{CA} + W_{FA}C_{FA} + W_{ADD}C_{ADD}] \qquad (2)$$

$$C_P^* = C_P + \frac{AP * \rho_{water}}{W_{total}} * C_{p,water} \qquad (3)$$

Where W is the mass of each ingredient in kg and c_p is the specific heat capacity of each ingredient in J/kg K, whereas thermal diffusivity (α) and effusivity (β) were calculated using Eq. 4 and 5 [30], respectively. The wet thermal diffusivity (α*) and effusivity (β*) were calculated using the same equations but using the saturated values of the components.

$$\alpha = \frac{\lambda}{\rho_d C_p} \quad (4)$$

$$\beta = \sqrt{\lambda \, \rho_d c_p} \quad (5)$$

The thermal resistivity was calculated using Eq. 6 as explained in Ref. [17] and [33].

$$R = \frac{d}{\lambda} \quad (6)$$

Where *R* is the thermal resistivity and it measures by $m^2/(K\ W)$ and *d*= material thickness (m). The λ value was measured as explained prior and the thickness was assumed 0.15 m that is commonly used for dwelling proposes in many countries which using concrete especially in roofing work.

4. Results and Discussion

4.1 Fresh Properties

The results of this work showed that there is a systematic reduction in slump flow (flowing ability) when incorporating rubber particles in all replacement types and percentages (see Fig. 3). However, with 5% wt replacement these reductions were insignificant where it can produce sufficient quality SCRC at all replacement types while with ≥10%wt replacement, a large decrement in flowability was noted in all substitution types corresponding to 31%, 26%,

and 23% reductions (at 15%wt addition) for FR, CR, and FCR types, respectively. The decrease in slump flow can be attributed to the surface texture and elasticity of the rubber particles, which could increase inter-particle friction during flow [33] and also absorb some of the kinetic energy. A general agreement with this finding has been published [33,34] and it confirms the negative effect of rubber aggregate on conventional concrete workability [24].

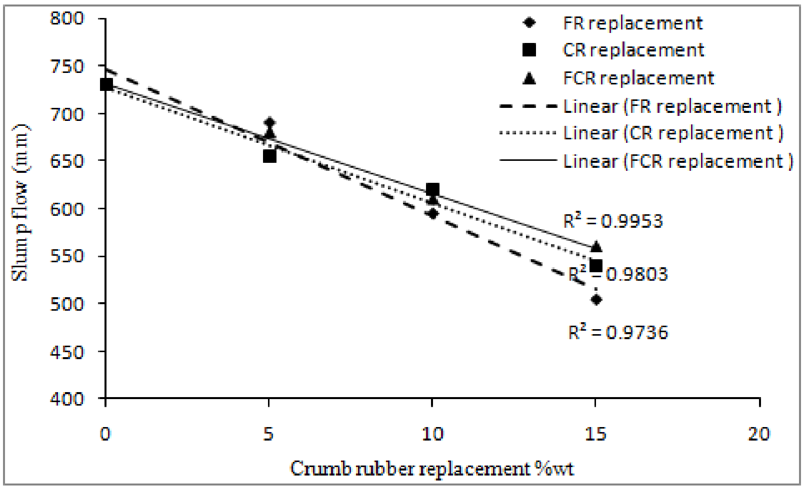

Fig. 3: Effect of crumb rubber replacement on slump flow

Fig. 4 illustrates that J-Ring Slump Flow (JRSF) followed the same general trend as slump flow. It was observed to reduce with %wt increase in rubber content, but the reduction was larger than for slump flow due to the effect of the obstacles (steel bars). On the other hand, with 15%wt rubber replacement the concrete spread was asymmetric (see Fig. 5-a). This occurred because of the non-uniform collapse of the cone due to the high mix viscosity which caused a buckling failure instead, as shown in Fig. 5 –b. Such behaviour was also observed by Grunewwald and Walraven [35], in steel fibre self-compacting concrete. In addition, Fig. 6 shows that the disparity between slump flow and JRSF increased with rubber content where it was ≥50mm at 15%wt replacement (N.B. mix should have ≤50mm to have good flow and passing [36]) which may result from blockage by the steel reinforcement or insufficient consolidation [26].

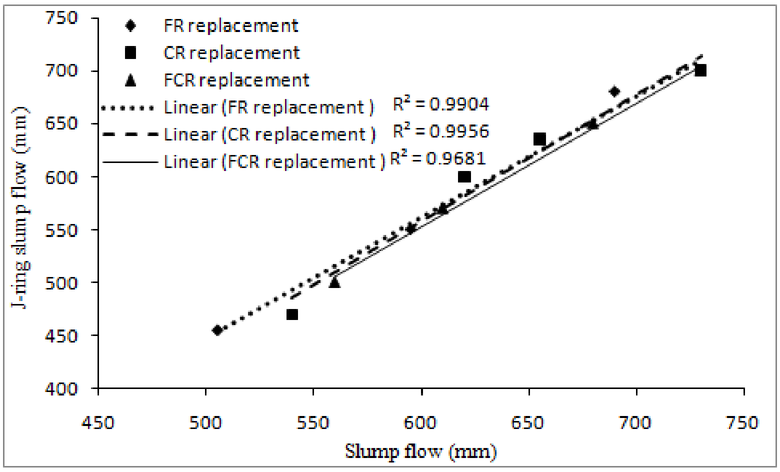

Fig.4: The relationship between slump flow and J-ring slump flow

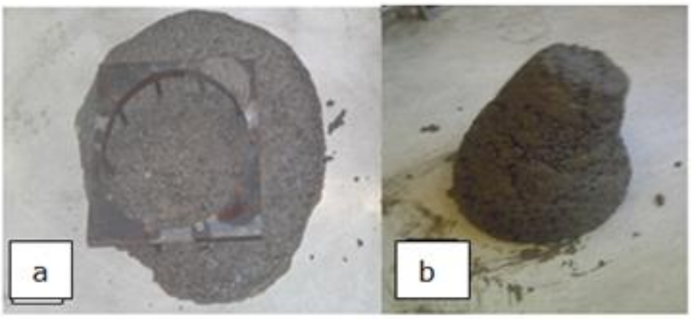

Fig.5: Spread and collapse behaviour of 15% wt crumb rubber replacement

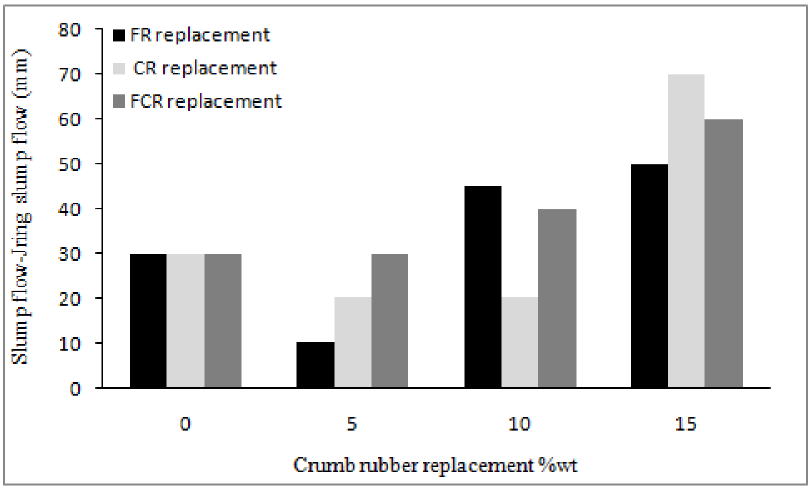

Fig.6: Effect of crumb rubber replacement on the difference between slump flow and JRSF

Concrete viscosity was assessed using the T_{50} and V-funnel tests. Table 4 and Fig. 7 clearly show that both T_{50} and V-funnel time increased with %wt rubber content for the same reasons as slump flow. Additionally, Bignozzi and Sandrolini [36] proved that there is an effective adhesion between the rubber particles and cement paste in SCRC which increases the mix viscosity. This may occur as a result of using the associated chemical and mineral admixtures. For example, T_{50} increased from 3s for plain SCC up to 17, 12, and 9s at 15%wt crumb rubber replacement for FR, CR, and FCR types, respectively. However, Table 4 shows that the largest values of T_{50} can be achieved with FR replacement and the lowest values with FCR replacement. Such behaviour can be attributed to the reduction in mortar (%FA) for the FR replacement resulting in a harsh mix, whereas for CFR replacement the reduction in CA and FA are in the same amount.

Table 4: Some fresh properties of SCRC mixes

	SCC Ref.	SCRCFR 5%	SCRCFR 10%	SCRCFR 15%	SCRCCR 5%	SCRCC R 10%	SCRCCR 15%	SCRCFCR 5%	SCRCFCR 10%	SCRCFCR 15%
T_{50}	3	5	11.5	17	4	6.8	12	3.5	5.8	9
T_{J50}	4	6.7	15.4	19	6	8.4	16	6.9	10.7	14
B_J	8.73	8.73	8.8	7.25	8.23	8.78	8.63	8.42	7.85	8.10

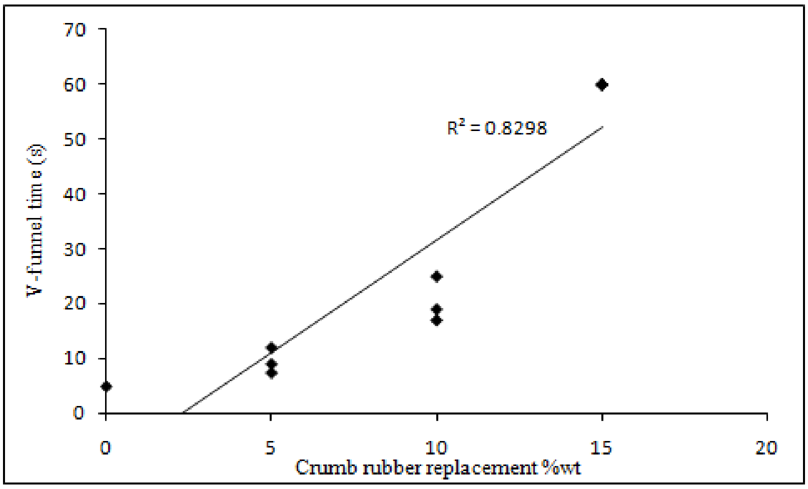

Fig.7: Effect of crumb rubber replacement on V-funnel time

Regarding the V-funnel time, although it increased with %wt rubber content, it was found that only mixes with ≤10%wt crumb rubber replacement satisfied the SCC requirement (see Table 1) whereas at 15%wt replacement the mixes failed by jamming as shown by Fig. 8. Such behaviour may be due to the significant air entrainment that occurs with rubber aggregate replacement, in addition to the reduced unit weight which may restrict consolidation and therefore flow through the funnel mouth. Furthermore, the angularity of the rubber aggregates compared to the rounded mineral aggregate being used would most likely increase mechanical interlock leading to jamming phenomena just above the funnel mouth. The blocking step B_J values indicated that although the SCRC jammed at 15%wt in the V-funnel test, there is a comparatively low risk of blocking when used with dense reinforcement ($B_J \leq 10$ mm) (see Table 4) making it suitable for some structural elements [26,34].

Fig. 8: Blocking behaviour of 15%wt crumb rubber content mixes

Interestingly, the Segregation Index, SI decreased sharply with %wt increase in rubber content (see Fig.9). It was ≤ 1% for all mixes with rubber except for 5%wt FR where it was 3.4% in comparison with 6.8% for plain SCC. This may be due to a partial reduction in mortar workability not fully compensated for by the increase in mix viscosity caused by rubber replacement. This behaviour was noted not only in FR replacement, where it was greatest, but also with CR and FCR replacement. Fig.10 illustrated that there was a negative correlation between viscosity measured by T_{50} and the segregation resistance.

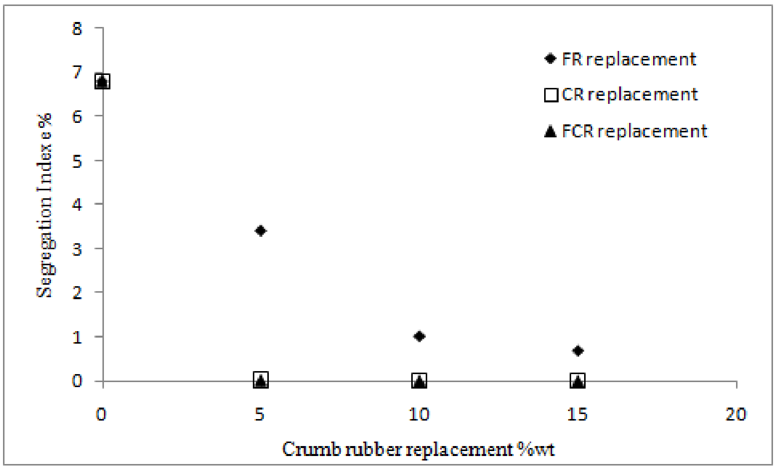

Fig. 9: Effect of crumb rubber replacement on the segregation resistance

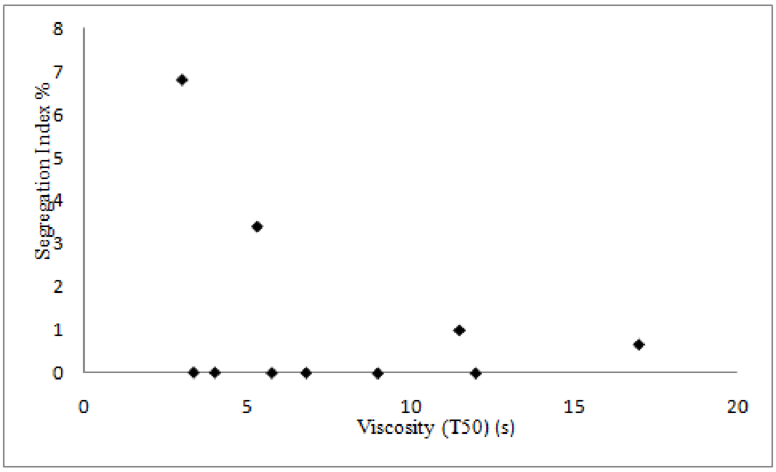

Fig. 10: The relationship between viscosity and segregation resistance

4.2 Unit Weight and Apparent Porosity

When crumb rubber aggregate is incorporated the unit weight decreased significantly (see Fig. 11), which can mainly be attributed to the significantly lower specific gravity of the crumb rubber (*G* = 1.12) and also to the increase in AP% caused by the air entrainment effect of the non-polar rubber particles during mixing. Nevertheless, the minimum density was 2151 kg/m^3 for 15%wt of FCR, which is suitable for most civil engineering applications including structural [11].

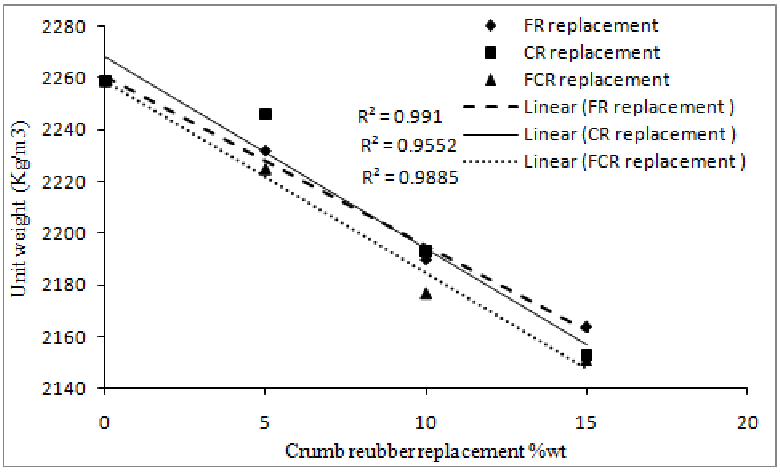

Fig. 11: Effect of crumb rubber replacement on unit weight

The air entrainment effect of crumb rubber addition increased the Apparent Porosity (%AP) for all mixes, as shown by Fig. 12. FR and FCR replacement types show almost identical behaviour in terms of air entrainment due to the sand replacement effect. Fig.13 shows a progressive reduction in bulk density with progressive increase in gravimetrically-determined apparent porosity. All SCRC mixes met the requirements of structural concrete since all compressive strengths were >17 MPa (see Table 3) and all AP <10% [11].

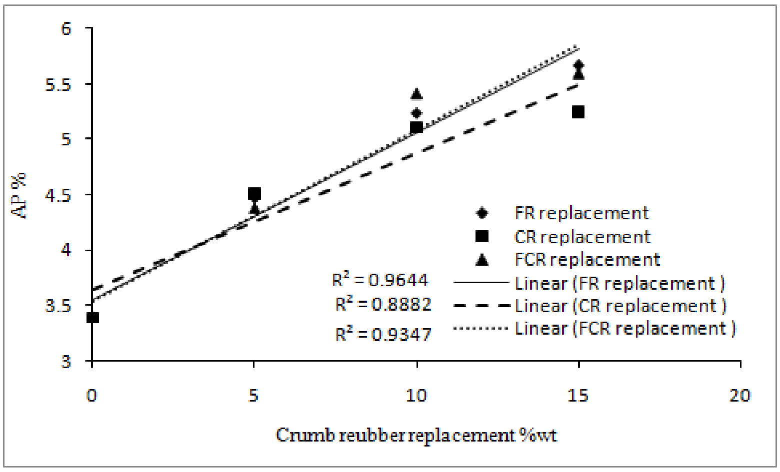

Fig. 12: Effect of crumb rubber replacement on the AP

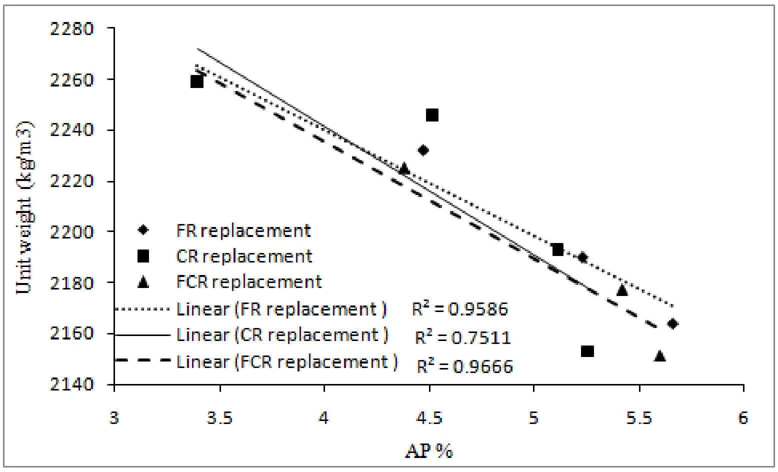

Fig. 13: The relationship between the AP and the unit weight

4.3 Thermo-Physical Properties

The thermal conductivity (λ) is defined as the coefficient governing heat flux by conduction through a material of known thickness and unit area, caused by a steady-state temperature gradient [15]. Concrete materials with low thermal conductivity are desirable for building applications in order to improve thermal insulation [37]. SCC is mainly used for structural functions and so SCRC could be employed in structural applications to reduce thermal bridging. Table 5 demonstrates that there is a general decrease in both λ* and λ with rubber substitution for all replacement types. Such reductions can be theoretically attributed to the lower unit weight of the SCRC mixes [17] as discussed in Section 4.2, where rubber replacement causes significant air-entrainment [24]. Additionally, the low λ of crumb rubber (0.11W/m K) compared with mineral sand (0.188 W/m K) and mineral gravel (0.269 W/m K), contributes to the global reduction in λ. Due to the air entrainment effect and resultant increase in %AP, λ is much lower than λ* for all SCRC mixes at the same %wt replacement because λ for air (0.025 W/m K) is much lower than λ for water (0.58 W/m K), and more importantly the convection transfer coefficient for liquid phases is significantly higher than for gas (air). From Table 5, it can be seen that FCR replacement gave the largest reductions

for the same percent crumb rubber replacement except at 15%wt, where the largest reduction (32.5%), in dry state, was found in FR replacement, which corresponds to the highest AP.

Table 5: Thermal properties of all tested mixes (* denotes saturated state)

	λ	λ*	c_p	c_p *	$\alpha \times 10^{-7}$	$\alpha^* \times 10^{-7}$	β	β*	*R*	*R**
	W/m K	W/m K	J/kg K	J/kg K	m^2/s	m^2/s	$J/s^{0.5}m^2K$	$J/s^{0.5}m^2K$	m^2/KW	m^2/KW
SCC	0.934	1.225	932	993	4.59	5.46	1378	1658	0.161	0.122
SCRCFR5%	0.816	1.031	945	1025	4.05	4.50	1282	1536	0.184	0.145
SCRCFR10%	0.790	1.016	958	1052	3.97	4.41	1253	1530	0.190	0.147
SCRCFR15%	0.630	0.884	971	1073	3.17	3.81	1117	1433	0.238	0.169
SCRCCR5%	0.868	1.036	944	1025	4.28	4.50	1326	1544	0.173	0.144
SCRCCR10%	0.766	1.017	955	1047	3.85	4.43	1234	1528	0.196	0.147
SCRCCR15%	0.690	0.838	967	1061	3.49	3.66	1167	1383	0.217	0.179
SCRCFCR5%	0.780	0.943	944	1023	3.88	4.14	1251	1465	0.192	0.159
SCRCFCR10%	0.721	0.852	963	1060	3.63	3.69	1196	1402	0.208	0.176
SCRCFCR15%	0.667	0.840	969	1086	3.39	3.59	1145	1401	0.225	0.178

The specific heat capacity (c_p), of SCRC increased with %wt crumb rubber replacement (see Table 5). Fig. 14 demonstrates that c_p increased generally with density decrease, where such behaviour can be attributed not only due to unit weight decrement with adding crumb rubber (Fig. 14) but also because of the high specific heat capacity of crumb rubber in comparison with natural aggregate (see Table 3). It was found that SCRC with 15%wt FCR offered the highest storage ability if both dry and wet states are considered.

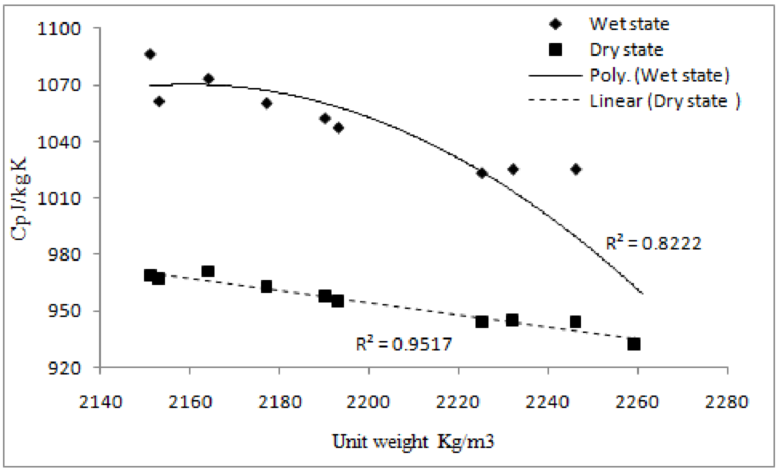

Figure 14: The relastionship between the unit weight and specific heat capacity

Thermal diffusivity (α) can be defined as the rate of heat that diffuses across an area of material (or combination of materials) in a specific time. It is measured by determining the differential in temperature and time between interior and exterior surfaces of a specimen [11]. Table 5 shows that α decreased significantly with crumb rubber substitution in all types and amounts of replacement. However, the lowest α value was found at 15%wt FCR in both dry and wet states. Regarding, thermal effusivity (absorptivity) β is important in terms of heating/cooling a surface, and also for the effects of fire [11]. It can be defined as the heat storage coefficient, i.e. the ability of a material to exchange heat with its surroundings. β continually decreased with the incorporation of crumb rubber in all replacement types and in both saturated and dry states. Unlike the diffusivity, the largest reduction was found at 15%wt FR in dry state and at 15%wt CR in wet state where they were 23% and 20% respectively, as Table 5 shows.

Heat transfer and storage in concrete materials considers three phases, i.e. gas (air and water vapour), liquid water and solid [16]. Thermal resistivity (*R*-value) is often used to evaluate the thermal performance of buildings, materials, or assemblies of materials [38]. The thermal

resistivity of SCRC increased significantly with crumb rubber substitution in both dry and wet states and for all types and amounts of replacement (see Table 5). Such behaviour can be attributed to the low thermal conductivity of crumb rubber aggregates and the increase in apparent porosity as a result of air entrapment caused by rubber addition. The greatest increase in *R*-value was found at 15%wt FCR replacement in both dry and saturated states, where it was 46% and 40% respectively (see Table 5)

5. Conclusions

Self-Compacting Rubberised Concrete (SCRC) can be produced with good filling ability (SF2 class) and typical flow rate (VS2) using 5%wt crumb rubber substitution and in all replacements types. It can have a low filling ability (SF1) class with 10%wt crumb rubber substitution in all replacements types. SCRC with 15%wt replacement cannot be considered as a true SCC mix in terms of its filling ability and flow rate, however it can be used as a high flowability concrete requiring only slight vibration as all SCRC mixes have good static segregation resistance SI2 (< 15%).

All SCRC mixes have densities >2000 kg/m^3 and <10% Apparent Porosity in addition to >17 MPa compressive strength. Consequently, all mixes can be used for structural concrete in various civil engineering applications. On the other hand, incorporating crumb rubber in SCC improved its thermal insulation properties by decreasing thermal conductivity, diffusivity, and effusivity, whilst increasing thermal resistivity and specific heat capacity for all types and amounts of replacement tested in this study. In particular, FCR replacement offered the best results in terms of thermal insulation besides the physico-mechanical performance. SCRC can be produced containing ~100 kg/m^3 crumb rubber with a slight increase in SP dose, and even up to 130 kg/m^3 crumb rubber (for structural applications) could be possible with mix design

modifications, e.g. cement paste volume. In both cases, SCRC will offer significant improvements in thermal insulation amounting to ~30% to 40% in dry state, and 44% to 46% in wet state, respectively. In addition to verifying the use of SCRC in structural elements, additional research in terms of durability and also full/large scale construction examples are important.

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6. References

[1] M. Ouchi and H. Okamura, Self compacting concrete: Development, present use and future, First International RILEM, 1999: p. 3-14.

[2] M. Ouchi and H. Okamura, Self- Compacting Concrete, Journal of Advanced concrete Technology. 1 (2003) 5-15.

[3] K.M.A. Hossain and M. Lachemi, Fresh, mechanical, and durability characteristics of self-compacting concrete incorporating volcanic ash, Materials in Civil Engineering. 22 (2010) 651-657.

[4] C. Parra, M. Valcuende, and F. Gómez, Splitting tensile strength and modulus of elasticity of self-compacting concrete, Construction and Building Materials. In Press, Corrected Proof.

[5] S.C Kou and C.S. Poon, Properties of self-compacting concrete prepared with coarse and fine recycled concrete aggregates, Cement and Concrete Composites. 31(2009) 622-627.

[6] T. Akram, S.A. Memon, and H. Obaid, Production of low cost self compacting concrete using bagasse ash, Construction and Building Materials. 23 (2009) 703-712.

[7] EFNARC, the European Guidelines for self-compacting concrete: specification, production, and use. (2005) 68.

[8] P. K. Mehta, Concrete technology for sustainable development, Concrete International 21 (1999) 226-235.

[9] V.M Malhotra, Role of supplemental cementing materials in reducing greenhouse gas emissions, in Concrete Technology for Sustainable Development in the 21st Century, E. Gjorv and K. Sakai (Eds), E & FN Spon: London 2000, pp. 226–235.

[10] F. Sanchez and K. Sobolev, Nanotechnology in concrete - A review, Construction and Building Materials. 24 (2010) 2060-2071

[11] A.M. Neville, Properties of Concrete, fourth ed, Longman, London, 1995.

[12] A.M. Rashad and S.R. Zeedan, The effect of activator concentration on the residual strength of alkali-activated fly ash pastes subjected to thermal load, Construction and Building Materials (2011). In Press, Corrected Proof.

[13] L.M. Al-Hadhrami, and A. Ahmad, Assessment of thermal performance of different types of masonry bricks used in Saudi Arabia, Applied Thermal Engineering. 29 (2009)1123-1130.

[14] Z, Dong et al., Development of thermal energy storage concrete, Cement and Concrete Research. 34 (2004) 927-934.

[15] M Alexander and S. Mindess, Aggregate in concrete, first ed. Taylor & Francis Group, London and New York, 2005.

[16]M. I. Khan, Factors affecting the thermal properties of concrete and applicability of its prediction models, Building and Environment. 37 (2002) 607-614.

[17] P. Sukontasukkul, Use of crumb rubber to improve thermal and sound properties of pre-cast concrete panel, Construction and Building Materials. 23 (2009)1084-1092.

[18] E. Ganjian, M. Khorami, and A.A. Maghsoudi, Scrap-tyre-rubber replacement for aggregate and filler in concrete, Construction and Building Materials. 23 (2009) 1828-1836.

[19] WRAP, Waste and resource action programme, in Tyre: reuse and recycling WRAP, 2007.

[20] C.G. Papakonstantinou and M.J. Tobolski, Use of waste tire steel beads in Portland cement concrete, Cement and Concrete Research. 36 (2006) 1686-1691.

[21] A, Turatsinze, S. Bonnet and J.L. Granju, Mechanical characterisation of cement-based mortar incorporating rubber aggregates from recycled worn tyres, Building and Environment. 40 (2005) 221-226.

[22] K. Paine and R.K. Daher, Research on new applications for granulated rubber in concrete, Proceedings Institution of Civil Engineers. 163 (2010) 7-17.

[23] K.B. Najim, Modulus of Elasticity and Impact Resistance of Chopped Worn–Out Tires Concrete, Iraqi Journal of Civil Engineering. 6 (2005) 83-96.

[24] K.B Najim and M.R. Hall, A review of the fresh/hardened properties and applications for plain (PRC) and self-compacting rubberised concrete (SCRC), Construction and Building Materials. 24 (2010) 2043-2051.

[25] K.B Najim and M. Hall, Mechanical and dynamic properties of self-compacting crumb rubber modified concrete, Submitted to Construction and Building materials Journal. Under review (2011).

[26] G.D Schutter and et al., Self-Compacting Concrete. Scotland Whittles Publishing, Dunthness, 2008.

[27] BS1881-114, Method for determination of density of hardened concrete, British standards Institute.1983.

[28] BS1881-116, Method for determination of compressive strength of concrete cubes, British standards Institute.1983.

[29] M. Hall and D. Allinson, Assessing the effects of soil grading on the moisture content-dependent thermal conductivity of stabilised rammed earth materials, Applied Thermal Engineering. 29 (2009) 740-747.

[30] M. R. Hall A. D, Assessing the moisture-content-dependent parameters of stabilised earth materials using the cyclic-response admittance method, Energy and Buildings. 40 (2008) 2044-2051.

[31] P. Keikha, M. Hall, and A. Dawson, Thermo-Physical Optimisation of Specialised Concrete Pavement Materials for Surface Heat Energy Collection and Shallow Heat Storage Applications, in Transportation Research Board. Annual Meeting.Washington DC, USA, 2011.

[32] R. McMullan, Environmental Science in Building. Third ed., Hampshire, MACMILLAN PRESS LTD, 1992.

[33] M Garros, A. Turatainze and J.-L.Granju, Effect of rubber aggregate from grinding of end-of-life tires on the properties of SCC, ACI Special publications. (2006) 77-187.

[34] A. Turatsinze and M. Garros, On the modulus of elasticity and strain capacity of Self-Compacting Concrete incorporating rubber aggregates, Resources, Conservation and Recycling. 52 (2008)1209-1215.

[35] S. Grünewald, and J.C. Walraven, Parameter-study on the influence of steel fibers and coarse aggregate content on the fresh properties of self-compacting concrete, Cement and Concrete Research. 31 (2001) 1793-1798.

[36] M.C Bignozzi and F. Sandrolini, Tyre rubber wastes recycling in self-compacting concrete, Cement and Concrete Research. 36 (2006) 735-739.

[37] X. Yungsheng and D.D.L. Chung, Effect of sand addition on the specific heat and thermal conductivity of cement, Cement and Concrete Research. 30 (2000) 59-61.

[38] PCI, committee on precast Sandwich panels. Stat-of-the-art of precast/prestressed sandwich wall panels, PCI Journal, 42 (1997) 92-134.