This is the peer reviewed author accepted manuscript (post print) version of a published work that appeared in final form in:

Youssf, Osama, Mills, Julie E, Benn, Tom, Zhuge, Yan, Ma, Xing, Roychand, Rajeev & Gravina, Rebecca 2020 'Development of crumb rubber concrete for practical application in the residential construction sector - design and processing', *Construction and Building Materials* vol. 260, article no. 119813, pp. 1-12

This output may not exactly replicate the final published authoritative version for which the publisher owns copyright. It is not the copy of record. This output may be used for non-commercial purposes. This version is licensed under a Creative Commons CC-BY-NC-ND 4.0 license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

The final definitive published version (version of record) is available at:
https://doi.org/10.1016/j.conbuildmat.2020.119813

Persistent link to the Research Outputs Repository:
http://researchoutputs.unisa.edu.au/11541.2/143321

General Rights
Copyright and moral rights for the publications made accessible in the Research Outputs Repository are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognize and abide by the legal requirements associated with these rights.

- Users may download and print one copy for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the persistent link identifying the publication in the Research Outputs Repository

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Development of Crumb Rubber Concrete for Practical Application in the Residential Construction Sector – Design and Processing

Osama Youssf [a,c,1], Julie E. Mills [a], Tom Benn [a], Yan Zhuge [a], Xing Ma [a], Rajeev Roychand [b], and Rebecca Gravina [b]

[a] UniSA STEM, University of South Australia, Adelaide, Australia
[b] School of Engineering, RMIT University, Melbourne, Australia
[c] Structural Engineering Department, Mansoura University, Mansoura, Egypt

ABSTRACT:

Extensive research has been carried out on crumb rubber concrete (CRC) in the past 10 years due to its potential as a sustainable and environmentally friendly material. Nevertheless, the practical use of this concrete class in the concrete industry to date has been very limited. This research is a part of a project that focuses on developing CRC for practical use in residential construction. The design and processing of CRC at three grades (20 MPa, 25 MPa, and 32 MPa) was carried out and the performance was investigated and compared with conventional concrete at the same strength levels. The study included three stages namely; selecting effective rubber particle size, designing and adjusting concrete mixes, and testing recommended mixes for practical applications. The slump, compressive strength, tensile strength, flexural strength, modulus of elasticity, shrinkage, creep, rubber pre-treatment effect and mixing order effect were measured. The results showed that within the crumb rubber size range used (0.15-2.36 mm) increasing the rubber particle size decreases the compressive strength losses. Compared to conventional concrete, the presence of 20% rubber as sand volume replacement decreased the 7-day/28-day strength ratio by values that ranged between 9% and 20%. CRC exhibited similar or lower shrinkage values, but higher creep strains compared to those of conventional concrete. The rubber pre-treatment enhanced the concrete slump, but no significant effect on compressive strength was observed. When the rubber was added together with water at the beginning without being premixed, the workability was low; however, when rubber was added and mixed dry or wet with the other materials, the CRC workability was enhanced.

Keywords: Rubber concrete; Mix design; Processing; Practicality; Mixing order; Shrinkage; Creep.

[1] Corresponding Author, E-mail: osama.youssf@mymail.unisa.edu.au

1 INTRODUCTION

In recent decades, managing the problem of what to do with used car tyres has created great interest. Every year, millions of tyres reach their practical use expiration worldwide. Of the expired tyres in Australia, 10% are recycled with re-use exportation of 30%, and hence illegal dumps, stockpiles, and landfill are taking the rest of these tyres [1, 2]. In Europe in 2010 the recovered end of life tyres comprised about 96% and only 4% were sent to landfills. The recovery included the re-use in energy production, materials recycling, reconstruction, and exportation [3]. The rapid accumulation of tyre waste is causing serious concerns about its impacts on human and environmental health. Waste tyres are difficult to degrade and are a significant source of environmental pollution. Therefore it is very important to accelerate the comprehensive utilization of waste tyre resources [4, 5]. Although, tyres can be recycled using several approaches, consuming recycled tyres in concrete has attracted a significant body of scientific research, especially the use of crumb rubber as concrete fine aggregate partial replacement, which has been termed crumb rubber concrete (CRC). The cost of obtaining or transporting regular concrete sand, and its increasing scarcity, is also adding research motivation to find another alternative to the river sand in concrete [6]. By recycling end of life tyres in concrete, valuable natural resources can be conserved, and the current tyre landfilling problem can be partially resolved [7, 8].

A significant body of small-scale or laboratory research on CRC has been carried out up to date, e.g. [9-14]. However, very limited research on large-scale structures or in-situ testing of CRC elements has been performed. Although, using rubber in concrete has raised concerns due to its adverse influence on its strength [15, 16], it can show enhanced concrete toughness, ductility, energy dissipation, damping ratio, and impact resistance [17-23]. To eliminate or reduce deficits caused by rubber in concrete, many options have been researched. Of these options, the most common ones were to add external additives to generally enhance concrete strength, and/or to pre-treat rubber particles. However, inconsistent and conflicting experimental outcomes have been reported up to date. Some researchers [9-11, 24-29] reported success in improving the CRC compressive strength by using several rubber pre-treatment approaches and/or external concrete additives. On the other hand, insignificant enhancement or strength losses have been reported by other researchers [12-14, 30-32] when using additives or rubber pre-treatment.

Some other studies used uncommon approaches to enhance the CRC properties with a variable degree of success in their findings. Pre-treating rubber by a silane coupling agent followed by cement paste coating showed concrete

strength increase up to 110% [33]; however, only 10-20% concrete strength increase was reported in [34] when they used a similar approach. A noticeable cement hydrates enhancement at the transition zone of the rubber/cement interfacial connection was observed when silane coupling agent was used as rubber pre-treatment [35]. Sulfuric acid (H_2SO_4) was able to double the strength of crumb rubber mortar [36]. Akinyele et al. [37] showed that aluminium, ferrous iron, silicon, oxygen, and calcium elements, decreased by increasing rubber content in concrete, but elements like carbon and sulphur increased, which act as impurities during the hydration process. Inorganic calcium chloride ($CaCl_2$) enhanced the CRC mechanical properties, but organic acidic and alkaline could not improve CRC properties effectively [30]. The CRC strength increased by 48.7% when oxidation and sulphonation of rubber particles was used [38].

For pre-mix concrete providers, it is unlikely that any researched rubber pre-treatment method will be an option used in preparing CRC for the concrete market if it is not cost-effective and practical. In addition to the construction economics, another critical issue that needs to be considered for this concrete class to be applied in the concrete industry is to provide practical mix designs to achieve adequate properties for both fresh and hardened concrete. Therefore, an economic and practical process for producing commercially viable CRC needs to be determined. This is to achieve the necessary workability and suitable mechanical properties for practical use.

This investigation focuses on developing CRC for practical use in residential construction. Large-scale CRC residential slabs were poured for several durability and on-site tests. The part of the overall project presented in this paper covers the design and processing of CRC at three grades (20 MPa, 25 MPa, and 32 MPa) and the comparison of the performance with conventional concrete at the same strength levels. This study was conducted in three stages, to select the appropriate crumb rubber size, and to design and test CRC mixes with compressive strengths commonly used in industry in various concrete applications (20 MPa, 25 MPa, and 32 MPa). From the trial mixes, nine mixes were selected and recommended for practical use. A set of measurements were carried out on the recommended mixes including shrinkage, creep, and mixing order effect. The next piece of research in this project will cover the durability of large-scale residential slabs made out of CRC.

2 EXPERIMENTAL PROGRAM

The experimental program conducted in this study progressed through several stages, namely: choosing the most effective crumb rubber particle size, adjustment of concrete mixes, final mix selection, and testing of selected mixes. The materials used in this study were selected based on the common materials utilized by the concrete industry (ready mix concrete companies) in Australia.

General Blended (Type GB) cement, 3.08 specific gravity, was used as the binder material. Stone sizes of 10 mm and 20 mm (specific gravity of 2.73 and unit weight of 1590 kg/m^3) were used as the coarse aggregate, while 5 mm river sand (specific gravity of 2.63 and unit weight of 1420 kg/m^3) was the fine aggregate. Crumb rubber (specific gravity of 0.97 and unit weight of 530 kg/m^3) was used as partial volume replacement of the concrete sand. It included four particle size categories with product names of #40mesh, #30mesh, 1-3mm, and 2-5mm. The size of the particles ranged between 0.150 mm and 0.425 mm for #40mesh rubber, between 0.30 mm and 0.60 mm for #30mesh rubber, between 0.60 mm and 1.18 mm for 1-3mm rubber, and between 1.18 mm and 2.36 mm for 2-5mm rubber. Particle size distribution of the aggregates used is shown in Fig. 1. Water reducer (WR) and high range water reducer (superplasticizer - SP) with respective specific gravities of 1.075 and 1.085, were used in this study. Air-entraining (AE) admixture with a specific gravity of 1.002 was also used in some concrete mixes.

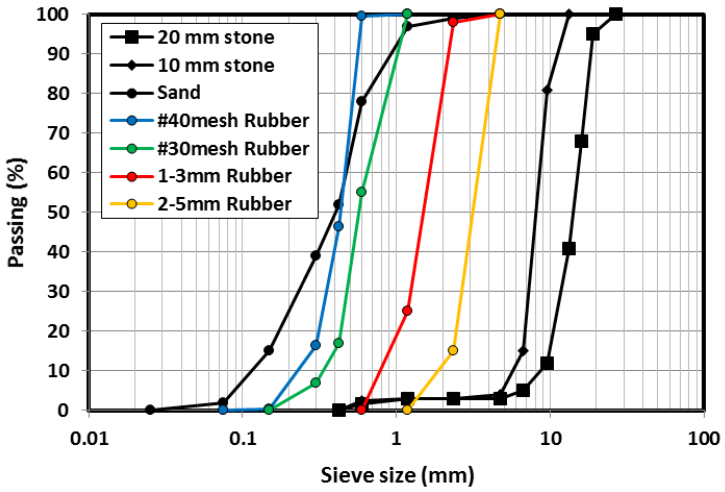


Fig. 1. Particles distribution of aggregates used.

2.1 *Stage-I: effective rubber particle size*

In this stage, the effect of using different crumb rubber particle sizes was investigated. Using 32 MPa control concrete, 20% of the sand volume was replaced by rubber with the four available rubber sizes described above. For this evaluation, the initial concrete slump and compressive strengths were measured. Concrete mixing in this stage commenced with mixing all dry materials, except cement, for 1 min, then ½ mixing water was added and mixed for 1 min. The mixing was then stopped for 2 min rest, and then remaining water, cement, and admixtures were added and mixed for another 2 min. Table 1 shows the details of mixes used in this stage. Fig. 2 shows the compressive strength and slump measured for each mix. Compared to the conventional concrete, the addition of rubber as sand replacement showed a significant change in the concrete slump and the compressive strength results. The slump decreased by 34% when using rubber size #40mesh and by 14% when using rubber size #30mesh. However, it increased by 34% when using 1-3mm, and by 43% when using 2-5mm. The slump decrease when using relatively fine crumb rubber particles and increase when using relatively coarse rubber particles might be attributed to the rubber surface area and presence of unburnt carbon black in rubber composition. The fine crumb rubber has relatively higher surface area than that of coarse crumb rubber with a higher possibility of unburnt carbon black exposure at the rubber surface. This results in a higher rate of water absorption from the available mixing water and hence, lower slump. However, the coarse rubber particles (that had fineness modulus higher than that of the substituted sand) has relatively less surface area, which increases the concrete mix wetness, and hence increases the slump. Other factors that might contribute to the lower slump when using fine crumb rubber are its relatively higher dispersion in the concrete matrix and the lightweight of the particles. This may affect the relative movement of the concrete components with the gravity direction and therefore, lead to lower slump.

The replacement of 20% of sand by rubber decreased its compressive strength regardless of the size of rubber used, due to the well-known reasons of poor bond performance at the rubber/cement interface and the weak inherent strength of the rubber particles. The big difference in materials stiffness between rubber and surrounding cement paste contributes to concrete strength reduction due to the relative deformation and early cracking. Within the crumb rubber size range used here (0.15-2.36 mm), increasing the crumb rubber particle size, decreases the strength losses, see Fig. 2. This was due to the higher fineness modulus of combined fine aggregates compared to that of sand only. Concrete strength increases by increasing its aggregates' fineness modulus [39].

Based on the outcomes of stage-I, crumb rubber size of 2-5mm was selected as the most effective size among the available sizes in the rubber market. This was due to its relatively higher workability and strength. In addition, this crumb rubber size is the most economical size compared with the other smaller sizes because of the lower processing energy and time required to produce this size.

Table 1: Concrete mixes of stage-I.

Mix code	*Rs (%)*	*Rubber size*	*Mix proportions (kg/m^3)*						*Initial slump (mm)*	*Compressive strength (MPa)*	
			Cement	*Sand*	*Stone*		*Rubber*	*Water*		*7 Day (SD)*	*28 Day (SD)*
					10 mm	*20 mm*					
CC32	0	--	333	818	454	445	--	213	105	31.6 (0.51)	41.2 (0.98)
CRC1	20	#40mesh	333	655	454	445	53.3	213	70	18.3 (0.68)	24.3 (0.12)
CRC2	20	#30mesh	333	655	454	445	53.3	213	90	19.5 (0.04)	25.0 (0.07)
CRC3	20	1-3mm	333	655	454	445	53.3	213	140	20.0 (0.40)	25.2 (0.10)
CRC4	20	2-5mm	333	655	454	445	53.3	213	150	20.5 (0.72)	26.0 (0.50)

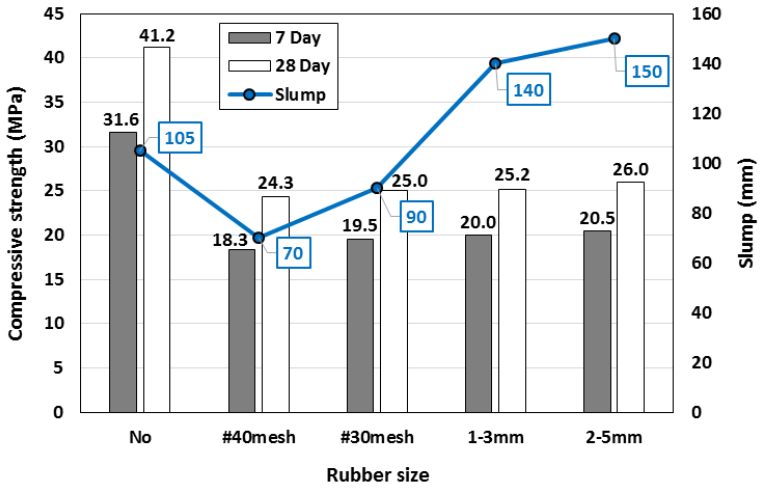


Fig. 2. Concrete slump and compressive strengths with different rubber sizes.

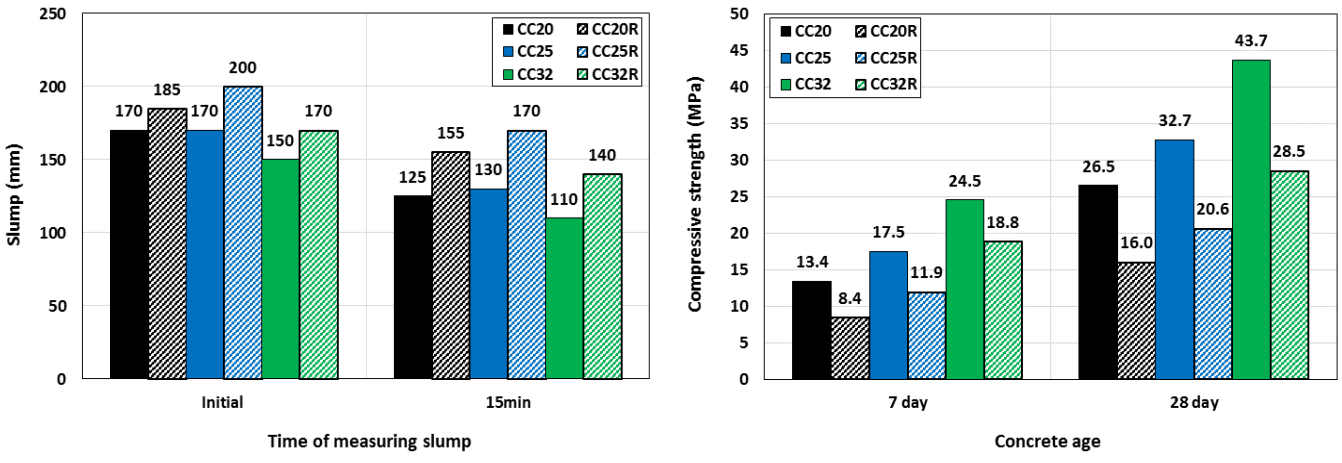
2.2 *Stage-II: mix adjustment and selection*

In order to map the required mix adjustments to achieve the targeted strengths (20 MPa, 25 MPa, and 32 MPa) after deciding to use rubber particle size of 2-5mm, it was important to know the level of strength loss and workability change when 20% of conventional concrete sand volume was replaced by rubber. This stage commenced with three conventional concrete mixes, recommended by the ready-mix company in Australia, in addition to three CRC mixes having 20% rubber content by sand volume. Table 2 shows the mixes used with the measured properties. Fig. 3 plots the slump and compressive strength of these initially tested mixes. Using rubber as partial replacement of sand, enhanced its initial (just after mixing completion) slump and 15 minute (after 15 min of mixing completion) slump.

This could be attributed to less water absorption ability of rubber particles compared with substituted sand. For 20 MPa, 25 MPa, and 32 MPa concrete grades, using rubber increased the initial slump by 9%, 18%, and 13%, respectively, and increased the 15 min slump by 24%, 31%, and 27%, respectively. The slump increase after 15 min was higher than the increase in the initial slump. This could possibly be due to the low rate of water absorption by rubber with time compared to that of concrete sand which keeps a high moisture content in the concrete mix for a longer time. With the addition of rubber in concrete mixes; CC20R, CC25R, and CC32R, a 40%, 37%, and 35% reduction in their respective 28 day compressive strength was observed, compared to those of the CC20, CC25, and CC32 control mixes, respectively.

Table 2: Concrete slump and compressive strength with and without rubber.

Mix	***Mix quantities (kg/m^3)***									***Slump (mm)***		***Comp. St. (MPa)***	
	Cement	***Water***	***W/C***	***Sand***	***Stone***		***Rubber***	***WR***	***AE***	***Initial***	***After 15min***	***7 day***	***28 day***
					10 mm	***20 mm***							
CC20	245	197.0	0.80	940	460	532	--	1.02	0.31	170	125	13.4	26.5
CC20R	245	196.9	0.80	752	460	531	69.9	1.02	0.31	185	155	8.4	16.0
CC25	285	203.4	0.71	885	458	539	--	1.11	0.31	170	130	17.5	32.7
CC25R	285	203.3	0.71	708	458	539	65.7	1.11	0.31	200	170	11.9	20.6
CC32	338	200.4	0.59	830	461	553	--	1.39	0.00	150	110	24.5	43.7
CC32R	338	200.3	0.59	664	461	553	61.7	1.39	0.00	170	140	18.8	28.5
WR	Water reducer				***AE***	Air-entraining				***W/C***	Water to cement ratio		



(a) (b)

Fig. 3. Effect of using 20% rubber at different concrete strengths on: (a) slump and (b) compressive strength

Based on the above measurements, adjustments were needed for CRC and traditional concrete mixes to be able to show workability and strength not only close to each other, but also close to the targeted slump and compressive strengths. This was considered in the following step in which several concrete mixes were proposed and tested to achieve similar concrete strengths for both conventional and CRC. To achieve the similar concrete strengths, the water/cement ratio, water reducer dosage, and superplasticizer dosage were the variables used in the adjustment process. Concrete mixing in this stage commenced with mixing all dry materials, except cement, for 1 min, then ½ mixing water was added and mixed for 1 min. The mixing was then stopped for 2 min rest, and then remaining water, cement, and admixtures were added and mixed for another 2 min. The concrete slump was measured as the initial slump and after 15 min slump. To accept the concrete workability, slump of not less than 90 mm after 15 min was targeted, as recommended by the ready-mix companies in Australia. During the waiting period before measuring the 15 min slump, there was no continuous mixing, the concrete was mixed again, for 2 min, before measuring the slump. This was to simulate the real concrete truck mixer which will usually keep on mixing concrete while transporting with a slow speed of 2-6 rpm; however, the laboratory pan mixer used in this stage had a speed of 25 rpm. At 7 and 28 days concrete ages, compressive strengths were also measured to follow up and verify the target strengths. Table 3 shows the details of the mixes tried in this stage.

Table 3: Trial concrete mixes in stage-II.

Mix	***Mix proportions (kg/m^3)***										***Slump (mm)***		***Comp. St. (MPa)***	
	Cement	***Water***	***W/C***	***Sand***	***Stone***		***Rubber***	***WR***	***SP***	***AE***	***Initial***	***After 15min***	***7 day***	***28 day***
					10 mm	***20 mm***								
CC20	240	216.2	0.90	919	450	519	0.0	0.00	0.00	0.30	145	100	12.6	22.7
CC20	237	224.6	0.95	909	445	514	0.0	0.00	0.00	0.30	210	165	10.4	21.4
CC20	245	197.0	0.80	941	460	532	0.0	0.66	0.00	0.30	145	110	13.9	24.1
CC25	279	219.5	0.79	868	449	529	0.0	0.00	0.00	0.30	160	120	15.7	29.6
CC25	285	203.5	0.71	885	458	539	0.0	0.56	0.00	0.30	170	115	17.7	30.7
CC32	333	212.2	0.64	818	454	545	0.0	1.18	0.00	0.00	185	115	24.0	37.9
CC32	334	212.3	0.64	819	455	546	0.0	0.00	0.00	0.00	135	105	19.4	32.9
CC32	336	204.9	0.61	826	459	551	0.0	1.01	0.00	0.00	185	145	23.9	38.9
CC32	333	212.0	0.64	817	454	545	0.0	1.33	1.33	0.00	235	130	25.0	35.8
CC32	337	205.0	0.61	826	459	551	0.0	0.51	0.00	0.00	165	110	23.9	38.9
CRC20	254	165.8	0.65	781	477	551	72.5	1.06	1.06	0.32	195	140	13.3	24.9
CRC20	256	161.6	0.63	784	479	554	72.8	1.06	1.60	0.32	180	100	15.4	25.6
CRC20	255	164.0	0.64	782	478	552	72.6	1.06	1.59	0.32	180	145	15.7	25.7
CRC20	251	176.1	0.70	771	471	544	71.6	1.05	1.05	0.31	180	135	14.3	24.4
CRC20	256	160.0	0.63	786	480	555	73.0	2.45	0.00	0.32	120	90	15.4	22.5

CRC20	256	159.8	0.63	785	480	554	72.9	3.73	0.00	0.30	150	95	15.4	22.7
CRC25	294	175.0	0.59	732	473	557	67.9	1.15	1.15	0.32	180	125	17.1	28.5
CRC25	292	180.4	0.62	727	470	554	67.5	1.14	1.14	0.31	220	170	18.4	30.6
CRC25	298	164.7	0.55	740	478	563	68.6	3.98	0.00	0.30	160	100	21.4	31.4
CRC32	342	190.4	0.56	672	467	560	62.4	1.41	0.00	0.00	115	80	19.6	33.6
CRC32	345	181.7	0.53	678	471	565	63.0	1.42	1.42	0.00	235	150	23.7	34.5
CRC32	349	173.2	0.50	685	475	570	63.6	3.96	0.00	0.00	175	95	26.1	36.6

WR Water reducer ***SP*** Superplasticizer ***AE*** Air-entraining

Based on the results from the trial mixes, six mixes were finalised as recommended mixes to suit industrial applications. The selection criteria were; success in passing 90 mm slump at 15 min, best 28 day compressive strength in each concrete grade, lowest amount of admixtures and avoiding mixes with superplasticizer as a preference of the concrete industry market due to its relatively high cost. Table 4 shows the selected mixes with similar compressive strengths. In addition, another three mixes were proposed for testing (CC20R, CC25R, and CC32R) having the same mix design as the conventional concrete ones (CC20, CC25, and CC32), but their sand was partially replaced by rubber aggregates at 20% volume, see Table 4. This was to study the performance of CRC at two strength levels through several measurements that will be discussed in the next section. The selected mixes had cement content of 245-350 kg/m^3, water/cement ratio of 0.5-0.8; water reducer admixture content of 0.15-1.45% of cement weight; and AE admixture content of 0.00-0.12% of cement weight.

Table 4: Recommended mixes for practical applications.

Mix	***Mix quantities (kg/m^3)***							
	Cement	***Water***	***Sand***	***Stone***		***Rubber***	***WR***	***AE***
				10 mm	***20 mm***			
CC20	245	197.0	941	460	532	0.0	0.66	0.30
CC25	285	203.5	885	458	539	0.0	0.56	0.30
CC32	337	205.0	826	459	551	0.0	0.51	0.00
CRC20	256	159.8	785	480	554	72.9	3.73	0.30
CRC25	298	164.7	740	478	563	68.6	3.98	0.30
CRC32	349	173.2	685	475	570	63.6	3.96	0.00
CC20R	245	197.0	785	460	532	72.9	0.66	0.30
CC25R	285	203.5	740	458	539	68.6	0.56	0.30
CC32R	337	205.0	685	459	551	63.6	0.51	0.00

WR Water reducer ***AE*** Air-entraining

2.3 *Stage-III: testing of recommended mixes*

In this stage, the recommended mixes that would be suggested to the concrete industry market were extensively tested to provide a big picture about their characteristics and performances. The concrete air content, 7 and 28 day compressive strength, 28 day indirect tensile strength, 28 day flexural strength, 28 day modulus of elasticity, and concrete drying shrinkages were measured for all the nine mixes shown in Table 4. In addition, the concrete creep was measured for 32 MPa concrete grade (mixes CC32, CRC32, and CC32R). Sodium hydroxide (NaOH) solution as a rubber pre-treatment effect was measured for the CC32R mix. NaOH solution with different concentrations of 10% and 50% by weight were proposed. The mixing order and concrete mixer type effects were measured on the concrete slump and compressive strength of CRC25 mix for better processing and practicality of CRC.

All tests were carried out according to the appropriate Australian Standards. Three specimens were tested for each measurement and average values were used in the comparisons. Concrete air content was measured using the pressure method according to AS 1012.4.1 [40]. Compressive strength, indirect tensile strength, and modulus of elasticity were measured using 100×200 mm cylinders. Flexural strength was measured using 100×100×470 mm prisms from each mix. Concrete shrinkage was measured using three prisms 75×75×280 mm for each mix at several concrete curing ages.

2.3.1 *Main characterstics*

The results of the measured characteristics for the recommended mixes are shown in Table 5 and Fig. 4. The results in Table 5 show the average values and standard deviations of three tested specimens per mix/measure. As shown in the table, all standard deviation values are small (maximum value recorded was 3.13) which demonstrates no dispersion of the data measured, as shown in Fig. 4. The target strengths at 28 days were achieved with 9-22% safety margins. Utilizing 20% rubber as a replacement of concrete sand decreased the 28 day compressive strengths by 18%, 20%, and 23% for 20 MPa, 25 MPa, and 32 MPa grade concrete mixes, respectively. The 7 day compressive strength trend for the tested mixes followed that of the 28 day compressive strength; however, it was observed that the presence of rubber decreased the 7-day/28-day strength ratio by values ranging between 9% and 20%, compared to that of corresponding conventional concrete. This may be attributed to the zinc stearate existence in the formulation of tyres [25, 41]. This zinc stearate migrates and diffuses in the mix creating a soap layer that could affect the

interaction between the cement particles and water which delayed the hydration reaction. In addition, the rubber particles have lower thermal conductivity than that of the replaced sand. This can reduce the overall concrete thermal conductivity which decreases the heat transfer rate within the concrete matrix, and hence less heat of hydration.

The tensile and flexural strengths showed good correlation with the corresponding compressive strengths in which the tensile strength was 8-11% and the flexural strength was 12-18% of the corresponding compressive strength. For the same strength grade mixes, the CRC showed a lower modulus of elasticity than that of the conventional concrete by 15.5%, 14.0%, and 9.4% for 20 MPa, 25 MPa, and 32 MPa concrete grades, respectively. This was because of the higher ductility and Poisson's ratio of CRC that resulted in relatively higher deformability of the concrete under the same stress and hence higher modulus of elasticity. As expected and due to the strength losses that occurred, replacing 20% of sand volume by rubber, decreased the modulus of elasticity by 28%, 20%, and 20% for 20 MPa, 25 MPa, and 32 MPa concrete grade mixes, respectively.

The measured air content displayed in Fig. 4(e) shows that the increase in concrete strength decreases its air content. This was due to the design of the current mixes, as shown in Table 4, which showed the water content increases with the increase in target strength. Replacing sand by rubber particles had an insignificant effect on the concrete air content. Both conventional concrete mixes (CC-mixes) and CRC mixes with reduced strength (CCR-mixes) had similar air contents. However, maintaining the CRC strength when replacing sand by rubber in CRC-mixes resulted in a significant increase in its air content, i.e. by about 2 times. This was mainly due to lower water content and the high dosage of WR used in these mixes. Less water content in the mix leads to less compaction and hence, more voids (air) within the concrete matrix. The WR in the concrete mix lowers the surface tension of the mixing water which produces millions of microscopic air bubbles and results in a significant increase in air content.

Table 5: Main characteristics of the recommended mixes.

Mix	***Air content***		***Compressive strength***				***Indirect tensile strength***		***Flexural strength***		***Modulus of elasticity***	
			7 day		***28 day***							
	%	***SD***	***MPa***	***SD***	***MPa***	***SD***	***MPa***	***SD***	***MPa***	***SD***	***GPa***	***SD***
CC20	5.4	0.05	16.9	0.40	22.3	0.04	2.4	0.20	3.8	0.33	31.0	0.96
CC25	4.3	0.00	21.6	0.70	28.5	0.10	3.3	0.08	5.0	0.33	31.4	3.01
CC32	2.9	0.00	32.3	0.30	39.0	0.62	3.8	0.41	4.8	0.42	36.1	1.27
CRC20	10.2	0.00	15.1	1.01	22.0	0.37	1.8	0.03	3.6	0.10	26.2	3.13
CRC25	9.5	0.00	19.6	0.86	28.7	0.43	2.7	0.24	4.2	0.51	27.0	1.15

CRC32	6.0	0.00	27.0	0.38	34.9	1.85	3.7	0.31	5.4	0.21	32.7	0.39
CC20R	5.0	0.46	11.0	0.38	18.2	0.37	2.0	0.18	3.0	0.16	22.3	1.48
CC25R	4.7	0.06	15.4	0.19	22.7	0.17	2.4	0.14	3.3	0.40	25.2	1.56
CC32R	2.6	0.05	21.3	0.17	30.0	0.72	2.7	0.23	3.9	0.13	28.9	0.62

SD Standard deviation

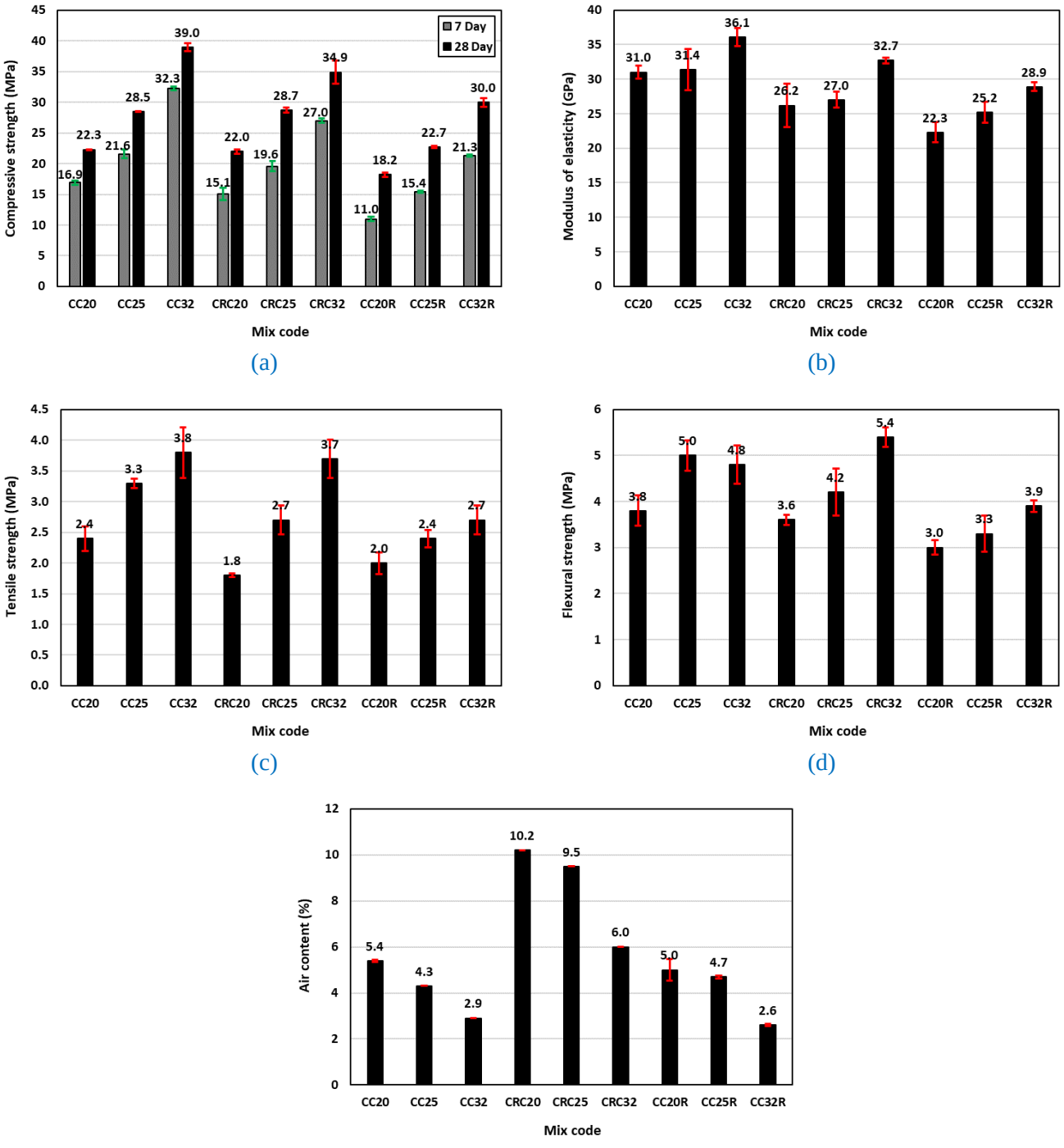


Fig. 4. Main characteristics of the recommended mixes: (a) compressive strength, (b) modulus of elasticity, (c) tensile strength, (d) flexural strength, and (e) air content.

2.3.2 *CRC drying shrinkage*

Table 6 and Fig. 5 show the drying shrinkage measured at different concrete ages for the studied mixes. The results in Table 6 show the average values, standard deviations, and coefficients of variation of three tested specimens per mix/measure. The coefficient of variation is the ratio of the standard deviation to the average value, which better represents the variation in the drying shrinkage values that are in microstrain (very small values). The recorded coefficients of variation demonstrate again the homogeneity of all measurements per mix. As shown in Fig. 5, with concrete curing age increase, the concrete drying shrinkage increased. Different shrinkage strain developments were observed. At the same concrete grade, CRC showed a similar shrinkage performance to that of conventional concrete at relatively early ages. However, at later ages less shrinkage by an average of 8% was evident. At the reduced strength, CRC showed less or similar shrinkage values to that of its corresponding conventional concrete mixes depending on the concrete grade. For 20 MPa grade concrete, the CRC exhibited lower shrinkage strain throughout the concrete age by an average of 15%. For 25 MPa grade, CRC showed less shrinkage at early ages by an average of 12% and similar shrinkage at later ages. For 32 MPa grade, CRC showed similar shrinkage values throughout the concrete age, except for an 11% increase at 14 day concrete age. Therefore, rubber has an overall insignificant effect on the shrinkage of concrete, and mostly it shows similar or lower shrinkage values compared to conventional concrete.

Table 6: Measured shrinkage of the recommended mixes in “microstrain” (μs).

Age	*Mix*	*CC20*	*CC25*	*CC32*	*CRC20*	*CRC25*	*CRC32*	*CC20R*	*CC25R*	*CC32R*
14 day	Shrinkage (μs)	282	316	297	299	319	331	234	254	329
	Standard deviation (μs)	7.79	10.04	6.44	29.20	26.80	13.34	17.19	1.89	23.59
	Coefficient of variation (%)	2.8	3.2	2.2	10.8	8.4	4.0	7.3	0.7	7.2
21 day	Shrinkage (μs)	419	419	471	406	423	475	310	397	461
	Standard deviation (μs)	15.03	3.99	25.60	30.00	27.60	47.01	78.50	15.76	31.54
	Coefficient of variation (%)	3.6	1.0	5.4	6.9	6.5	9.9	25.3	4.0	6.8
28 day	Shrinkage (μs)	524	505	530	525	480	483	477	515	526
	Standard deviation (μs)	52.57	8.11	3.20	1.60	28.80	71.88	1.73	6.91	41.25
	Coefficient of variation (%)	10.0	1.6	0.6	0.3	6.0	14.9	0.4	1.3	7.8
56 day	Shrinkage (μs)	623	637	668	573	568	585	573	626	678
	Standard deviation (μs)	21.88	1.89	5.20	8.00	22.00	65.59	15.75	9.52	38.23
	Coefficient of variation (%)	3.5	0.3	0.8	1.0	3.9	11.2	2.7	1.5	5.6

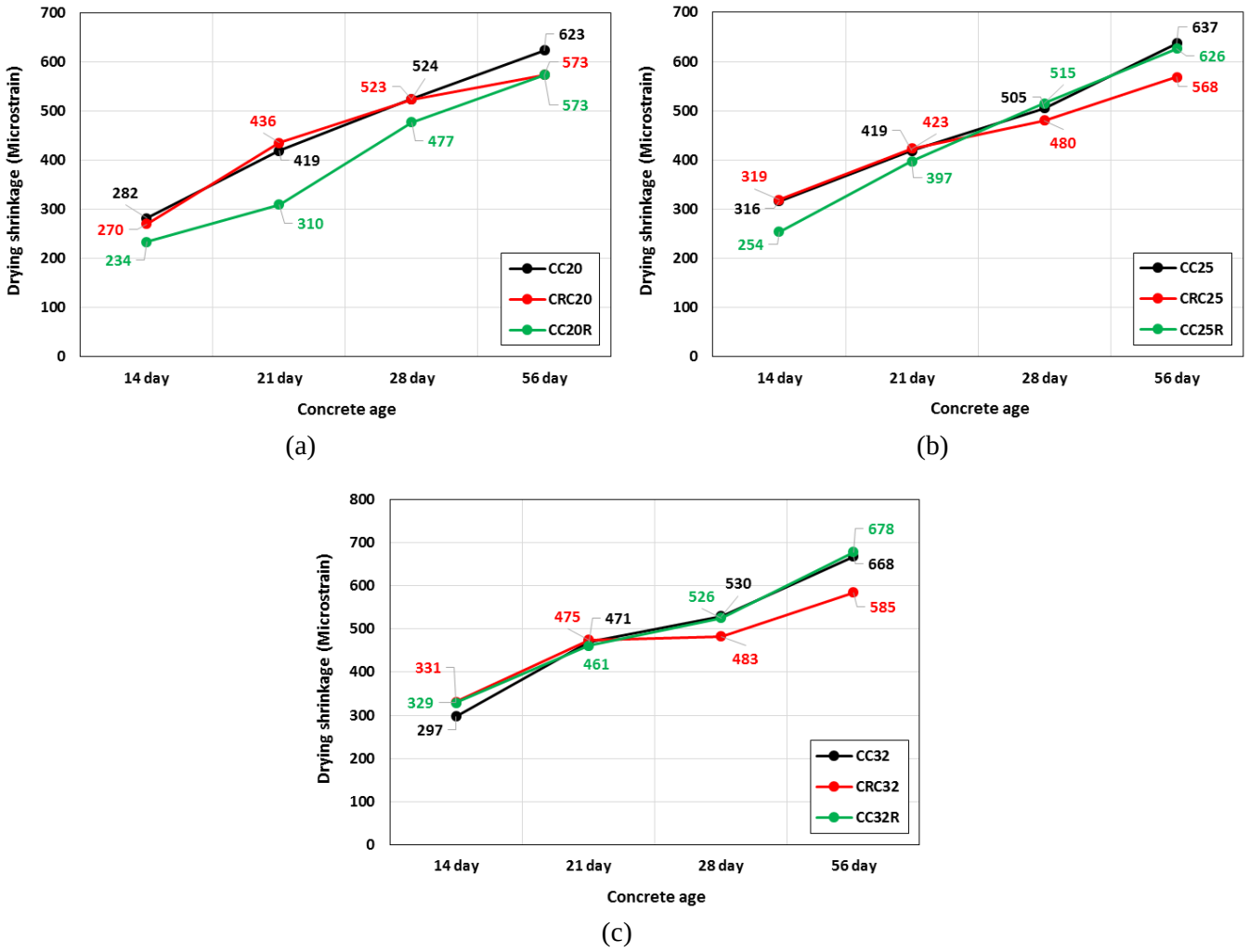


Fig. 5. Drying shrinkage for concrete grades: (a) 20 MPa, (b) 25 MPa, and (c) 32 MPa.

2.3.3 *CRC creep*

Concrete creep has a significant effect on structural integrity due to its influence on the structure deformation and stress distribution [42]. Very limited data about the creep performance of CRC are available in the literature. Adamu et al. [43] reported up to 81% increase in the creep strain and about double the creep coefficient when replacing 10% of concrete sand volume by crumb rubber. In this study, the concrete creep test was carried out for concrete mixes CC32 and CC32R according to AS 1012.16 [44] at a concrete age of 28 days. Two sets of three 100 × 200 mm concrete cylinders (loaded creep specimens) were tested for each mix and average results were used for comparisons. For each mix, two cylinders were also prepared for drying shrinkage measuring (unloaded control specimens). All specimens were cured in a 23 °C room for 24 hrs, then for 6 days (7 days from mixing) in moist condition (water bath), and then for an additional 21 days (28 days from mixing) in dry condition (23 °C room). Creep and control specimens were prepared by grinding their ends and attaching demec points to the specimen at mid-height for axial

strain measurements at a gauge length of 100 mm and 120° apart. Each creep specimen set was centralized and axially loaded in a creep rig by 40% of the concrete ultimate 28 day compressive stress for one complete year. The axial strains were measured immediately before and after loading, at 2 hr, 6 hr, and then once daily for 7 days, then once a week for 4 weeks, and then once a month for 11 months. The creep test was conducted in curing room with 55% relative humidity and 23 °C temperature. This included loaded and unloaded control specimens. The applied loads were re-adjusted periodically to overcome the load relaxation that occurs due to the creep deformation. The load re-adjustments were carried out once a day in the first loading week, then once a week in the first loading month, and then every month till the end of the test. Fig. 6 shows the details of the creep test preparation and setup. The net creep strain ($\boldsymbol{\varepsilon_c}$), creep strain per applied stress ($\boldsymbol{\varepsilon_c/MPa}$), and the creep coefficient ($\boldsymbol{\varphi}$) throughout the loading life were determined using the following formulae:

$$\boldsymbol{\varepsilon_c = \varepsilon_t - \varepsilon_s - \varepsilon_i} \quad \text{Eq. 1}$$

$$\boldsymbol{\varepsilon_c/MPa = \frac{\varepsilon_c}{\sigma}} \quad \text{Eq. 2}$$

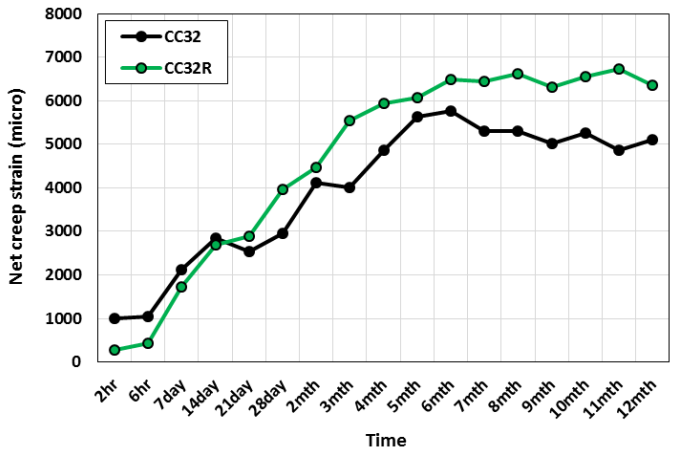
$$\boldsymbol{\varphi = \frac{\varepsilon_t - \varepsilon_s}{\varepsilon_i}} \quad \text{Eq. 3}$$

where, $\boldsymbol{\varepsilon_t}$ is the average total measured strain in the loaded specimens, $\boldsymbol{\varepsilon_s}$ is the average measured drying shrinkage strain in the unloaded specimens, $\boldsymbol{\varepsilon_i}$ is the average instantaneous measured strain in the loaded specimens, and $\boldsymbol{\sigma}$ is the applied stress in MPa on the loaded specimens.

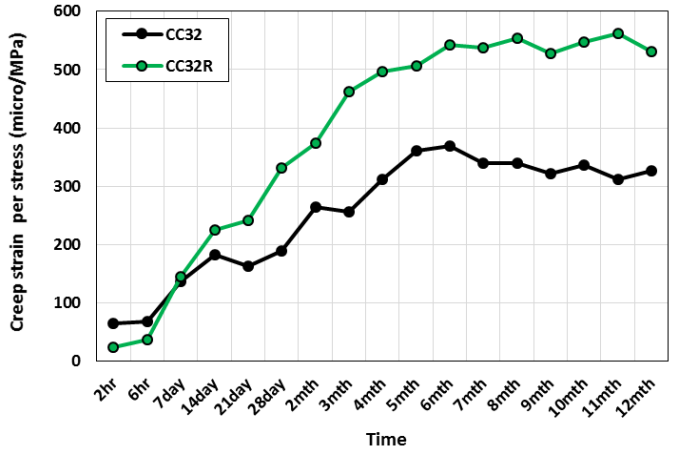


Fig. 6. Creep test preparation and setup.

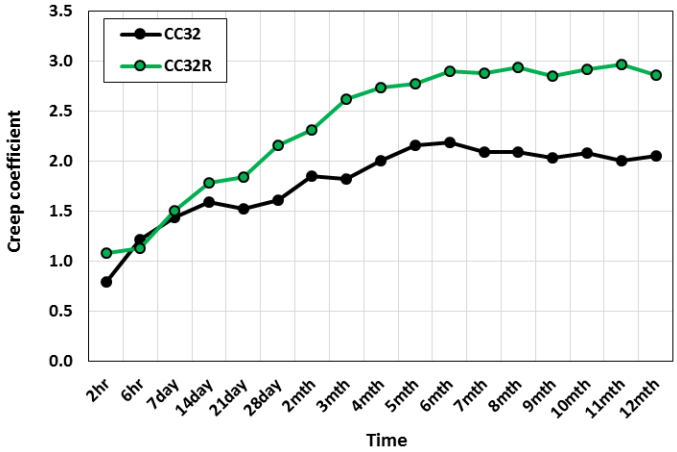
The determined creep properties are plotted throughout one year period of loading in Fig. 7. As shown in Fig. 7(a), the $\boldsymbol{\varepsilon_c}$ for both conventional concrete and CRC increased almost linearly up to 5 month loading period. Beyond that, $\boldsymbol{\varepsilon_c}$ showed constant values till the end of the test life. This is because at early ages concrete has relatively lower compressive strength which allows for easier deformation under constant load. No significant difference was observed in $\boldsymbol{\varepsilon_c}$ between conventional concrete and CRC at early loading ages up to 28 days. However, CRC started to show relatively higher $\boldsymbol{\varepsilon_c}$ values at later loading ages by an average of 24%. This was attributed to two factors namely; CRC compressive strength, and the modulus of elasticity of the rubber particles. The low CRC compressive strength in addition to the low modulus of elasticity of rubber particles cause lower overall concrete modulus of elasticity, and hence higher strain under load. Similar behaviours were recorded when relating creep strain to the applied stress as shown in Fig. 7(b). However, higher $\boldsymbol{\varepsilon_c/MPa}$ values were recorded for CRC compared to those of conventional concrete from after 14 days of loading. The average $\boldsymbol{\varepsilon_c/MPa}$ for CRC was 58% higher than that of conventional concrete due to the relatively higher $\boldsymbol{\varepsilon_c}$ values and lower applied stress (40% of ultimate stress) of CRC. The creep coefficient expresses the creep intensity and is an important parameter for concrete design, especially for prestressed elements. Fig. 7(c) shows the variation of $\boldsymbol{\varphi}$ with loading time for the tested mixes. Similar $\boldsymbol{\varphi}$ values were observed for both conventional concrete and CRC up to 7 day loading time. Beyond that, the $\boldsymbol{\varphi}$ increased up to 5 month loading time, and then stayed constant until the end of the test loading period. However, the $\boldsymbol{\varphi}$ of CRC increased in a higher rate than that observed for traditional concrete. Between 7 days and 12 month loading time, the average increase in the $\boldsymbol{\varphi}$ was 32% when using CRC compared to conventional concrete. From the above measurements, it is recommended that the creep characteristics and performance of CRC should be considered when employing this type of concrete in structures subjected to high loads, such as columns and footings in high rise buildings. However, it would attract less concern if CRC is used in lightly loaded structures, such as residential footings for single storey buildings.



(a)



(b)



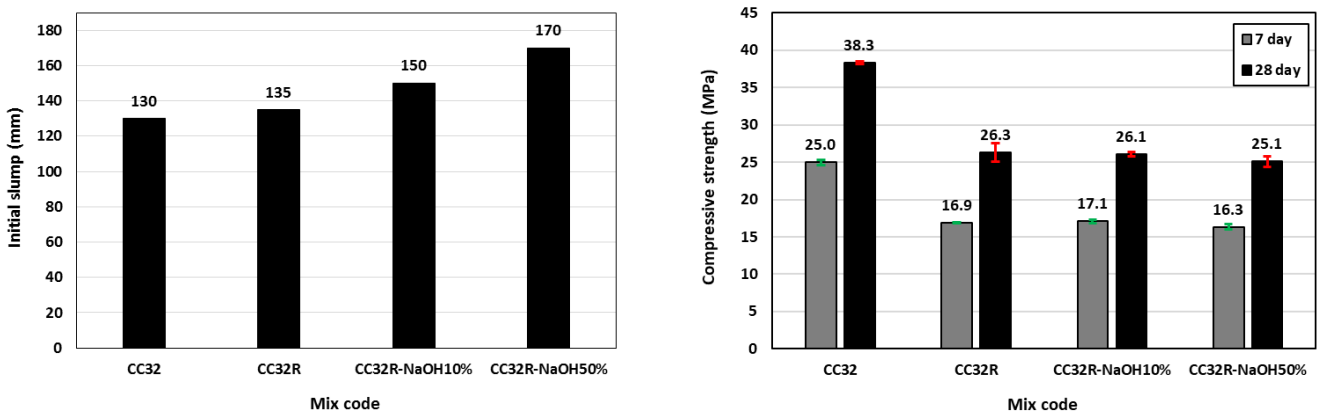
(c)

Fig. 7. Creep properties of tested mixes: (a) net creep strain, (b) creep strain per applied stress, and (c) creep coefficient.

2.3.4 *Rubber pre-treatment effect*

Sodium hydroxide (NaOH) solution is a common pre-treatment chemical in the literature, which has the ability to remove impurities and soap materials from the rubber surface that is presented in its formulation [45]. However, the effectiveness of NaOH solution in treating rubber surface in the literature has been scattered and inconsistent [13, 24, 26, 30]. Since this current research was aimed at processing CRC for practical use, the influences of pre-treating rubber with NaOH solution on concrete strength and initial slump was investigated for the CC32R mix. The proposed concentrations of the NaOH solution were 10% and 50% by weight. The treatment commenced with soaking rubber in the solution for ½ hr. the rubber was then tap water washed to reduce its pH to 7, then air dry was used before using rubber in concrete mixes.

Fig. 8 shows the variation of concrete slump and strength of the tested mixtures. The concrete slump was measured one time per mix and the compressive strength was taken as the average of three specimens per mix. The maximum standard deviation in compressive strength determined for these mixes was as small as 0.70, which demonstrates the homogeneity of the specimens taken from the same mix. The pre-treatment of rubber improved the concrete workability by 11% and 26% when using 10% and 50% NaOH solution, respectively. This may be due to the smoother surface of pre-treated rubber that decreases the friction between the particles and other concrete components, and therefore workability increases. No significant effect was recorded for compressive strength enhancement at 7 or 28 day of concrete age, with applying the NaOH solution treatment. This can be due the surface cleaning caused by the treatment, which is only able to enhance the adhesion at the interface between rubber and cement. However, the rubber particles' stiffness is much lower than other ingredients in concrete and the pre-treatment does not enhance the material stiffness, resulting in lower contribution towards the resistance to the stress transfer which causes strength reduction. From a practical point of view, it is recommended that CRC with its relatively lower strength would be utilized as it is without rubber pre-treatment, and this class of concrete should be employed in practical applications that suit this reduced strength, such as residential concrete slabs.



(a) (b)

Fig. 8. Effect of NaOH on CRC: (a) initial slump and (b) compressive strength.

2.3.5 *CRC mixing order*

In order to test CRC in practical conditions, mix CRC25 was prepared in the concrete plant and delivered by a concrete rotating drum truck to a selected site, 15 min drive away. The mixing procedures followed in the concrete plant were uncommon because the rubber aggregate was loaded first in the truck with part of the mixing water, and then the other concrete ingredients were added and mixed as usual. There was no negative comment on the mix-ability and deliverability of CRC; however, the concrete workability was lower than expected (50 mm slump) when it arrived at the site. This motivated the authors to investigate the mixing order effect on the concrete workability and strength using two different concrete mixers (different mixing mechanisms) namely; a tumble mixer (shearing and diffusive mixing mechanism) and a pan mixer (centrifugal force with rotating paddles mixing mechanism). Five different sequences of adding the materials, with constant mixing time and three stages, were considered in this research as follows:

- Order 1 (O1): mix all dry materials, except cement, for 1 min, then ½ mixing water was added and mixed for 1 min. The mixing was then stopped for 2 min rest, and then remaining water, cement, and admixtures were added and mixed for another 2 min.
- Order 2 (O2): load rubber and ¾ water without mixing for 2 mins; add stone and sand, and mix for 2 mins; then the remaining water, cement, and admixtures were added and mixed for another 2 min.
- Order 3 (O3): load stone, sand, and ¾ water without mixing for 2 mins; add rubber, and mix for 2 mins; then the remaining water, cement, and admixtures were added and mixed for another 2 min.

- Order 4 (O4): load rubber, sand, stone, and ¾ water without mixing for 2 mins; mix for 2 mins; then the remaining water, cement, and admixtures were added and mixed for another 2 min.
- Order 5 (O5): mix dry cement, rubber, sand, stone, and ¾ water for 2 mins. The mixing was then stopped for 2 min rest, and then remaining water and admixtures were added and mixed for another 2 min.

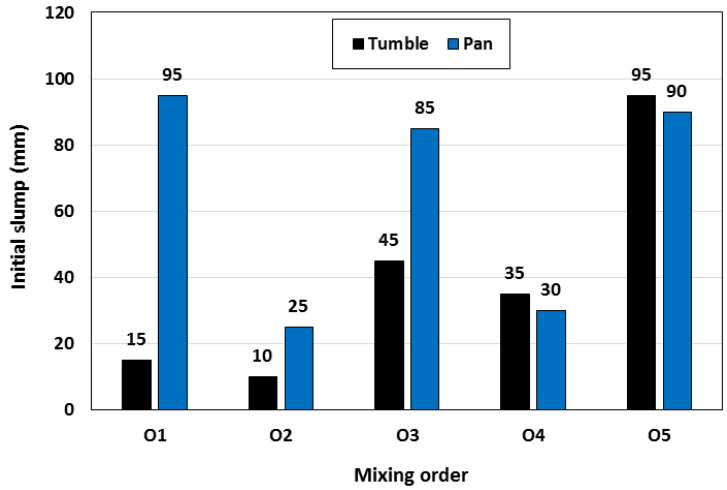
The results of the mixing order effect are shown in Table 7 and Fig. 9. The concrete slump was measured one time per mix and the compressive strength was taken as the average of three specimens per mix/measure. The maximum standard deviation (see Table 7) in compressive strength determined for this set of mixes was as small as 0.82, which shows that no significant dispersion occurred in the results, as can be seen in Fig. 9(b). The mixing order and mixing mechanism showed significant effects on CRC slump. The sequences of material addition that included rubber added with water from the beginning without mixing, exhibited low workability. However, when rubber was added and mixed dry or wet with the other materials, the CRC workability was better. The pan mixer showed similar or better slump to that showed by the tumble mixer throughout the sequence of material addition trials. This may be attributed to the relatively high energy exerted by the pan mixer compared to that of the tumble mixer that is mixing mainly based on the gravity effect. This helps to better disperse the concrete components including water and admixtures, and hence achieves better slump. The mixing order and mixing mechanism showed variable effects on CRC compressive strength and the target strength could not be achieved in some cases. Generally, the tumble mixer showed better CRC strength than that shown by the pan mixer, which is a promising observation as the tumble mixer has the closest mixing mechanism to that of the concrete truck. Therefore, from the above results, it was observed that order #5 is the best selection to follow for CRC as it showed the highest slump using the tumble mixer (which simulates the truck mixer) and achieved the target 28 day compressive strength (25 MPa).

The conclusion from the above laboratory trials was then practically applied to $1m^3$ of concrete from mixes CRC25 and CC20R to make sure that the mix designs worked well when using the truck mixer from the concrete plant. The slump was measured three times for those mixes and the average of the recorded initial slumps was 150 mm and 220 mm for CRC25 and CC20R mixes, respectively, which were even better than the ones observed from the laboratory testing level.

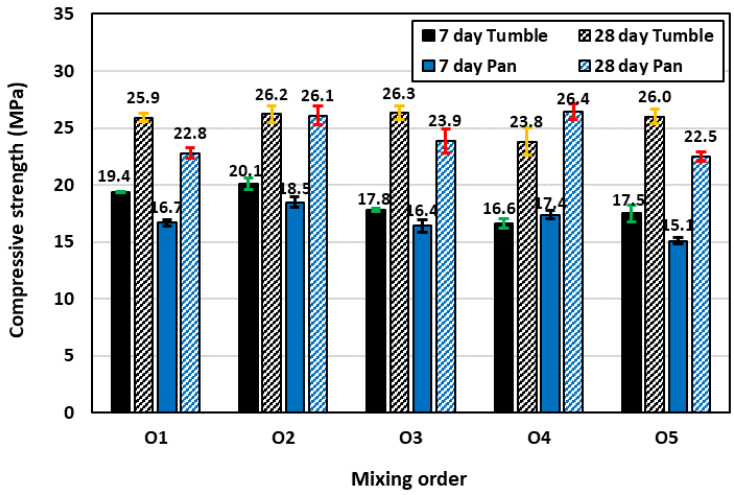
Table 7: CRC mixing order effect.

Mixing order	*Tumble mixer*					*Pan mixer*				
	Slump (mm)	*Compressive strength*				*Slump (mm)*	*Compressive strength*			
		7 day		*28 day*			*7 day*		*28 day*	
		MPa	*SD*	*MPa*	*SD*		*MPa*	*SD*	*MPa*	*SD*
O1	15	19.4	0.06	25.9	0.36	95	16.7	0.28	22.8	0.47
O2	10	20.1	0.47	26.2	0.69	25	18.5	0.43	26.1	0.82
O3	45	17.8	0.15	26.3	0.59	85	16.4	0.56	23.9	1.06
O4	35	16.6	0.42	23.8	1.21	30	17.4	0.38	26.4	0.69
O5	95	17.5	0.74	26.0	0.61	90	15.1	0.27	22.5	0.41

SD Standard deviation



(a)



(b)

Fig. 9. Mixing order effect on CRC: (a) workability and (b) compressive strength.

3 SUMMARY AND CONCLUSIONS

This research was aimed at moving CRC to concrete industry practical use. A wide-ranging experimental investigation on processing of CRC for practical use is presented in this paper. The study started with many trial mixes to achieve CRC with the most common strengths in concrete applications in the residential construction sector (20 MPa, 25 MPa, and 32 MPa). A range of measurements were carried out on selected CRC mixes including; air content, compressive strength, tensile strength, flexural strength, modulus of elasticity, creep, shrinkage, rubber pre-treatment effect, and mixing order effect. The main conclusions and recommendations of this study are summarised below:

1. Using #40mesh and #30mesh rubber decreased concrete slump by 34% and 14%, respectively; however, using 1-3mm and 2-5mm rubber enhanced concrete workability by 34% and 43%, respectively, compared to that of conventional concrete. Increasing the crumb rubber particle size decreases the compressive strength losses.
2. The concrete initial and after 15 min slumps were enhanced by using rubber. The slump increase after 15 min was higher than the increase in the initial slump. The presence of rubber in concrete decreased the 7-day/28-day strength ratio by values that ranged between 9% and 20% compared to that of conventional concrete.
3. At the same concrete grade, CRC showed higher air content and less modulus of elasticity than the corresponding conventional concrete. Rubber has an overall insignificant influence on the shrinkage of concrete and mostly it showed similar or lower shrinkage values compared to that of conventional concrete.
4. At 32 MPa concrete grade, CRC showed higher creep strains and creep coefficient than the corresponding conventional concrete by averages of 24% and 32%, respectively. It is recommended that the CRC creep characteristics and performance should be considered when employing that type of concrete in structures subject to high loads. However, it would attract less concern if CRC is used in lightly loaded structures, such as residential footings for single storey buildings.
5. The rubber pre-treatment enhanced the concrete slump by 11% and 26% when using 10% and 50% NaOH solutions, respectively. However, no significant effect on compressive strength was observed.

6. When rubber had water added from the beginning of the mix process it exhibited low workability. However, when rubber was added and mixed dry or wet with the other materials first, the CRC workability was better. A tumble mixer showed better CRC strength than the pan mixer, which is a promising observation as the tumble mixer has the closest mixing mechanism to that of the concrete truck in practical applications.

4 Acknowledgment

The authors would like to acknowledge the fund provided by the Australian Research Council (ARC-LP160100298) and industry partners for this project. The industry partners are; Tyrecycle Pty Ltd, Tyre Stewardship Australia, ResourceCo Pty Ltd, FMG Engineering Pty Ltd, and Ancon Beton. The materials donations by ResourceCo Pty. Ltd., Adelaide Brighton Cement Pty. Ltd., and Tyrecycle Pty. Ltd., are greatly appreciated. The authors also would like to thank the support of lab staff member and PhD students who helped in this work: Dr. Henry Senko, Mr. Tim Golding, Mr. Ian Whitehead, Ms. Ou Yi, and Mr. Essam Eltayeb.

5 REFERENCES

[1] Tyre Stewardship Australia, Tyre Product Stewardship Scheme "https://www.tyrestewardship.org.au/about-tsa/tyre-product-stewardship-scheme", 2019.
[2] O. Youssf, R. Hassanli, J.E. Mills, Y. Zhuge, Axial Compression Behaviour of Hybrid Double-Skin Tubular Columns Filled with Rubcrete, Journal of Composites Science 3(2) (2019) 62.
[3] ETRMA - European Tyre Rubber Manufactures Association, European tyre and rubber industry - Statistics "http://www.etrma.org/statistics-2", 2014.
[4] X. Shu, B. Huang, Recycling of waste tire rubber in asphalt and portland cement concrete: An overview, Construction and Building Materials 67 (2014) 217-224.
[5] R. Roychand, R.J. Gravina, Y. Zhuge, X. Ma, O. Youssf, J.E. Mills, A comprehensive review on the mechanical properties of waste tire rubber concrete, Construction and Building Materials 237 (2020) 117651.
[6] T. Gupta, S. Chaudhary, R.K. Sharma, Assessment of mechanical and durability properties of concrete containing waste rubber tire as fine aggregate, Construction and Building Materials 73(0) (2014) 562-574.
[7] G. Li, G. Garrick, J. Eggers, C. Abadie, M.A. Stubblefield, S.S. Pang, Waste tire fiber modified concrete, Composites Part B: Engineering 35(4) (2004) 305-312.
[8] O. Youssf, J.E. Mills, R. Hassanli, Assessment of the mechanical performance of crumb rubber concrete, Construction and Building Materials 125 (2016) 175-183.
[9] I. Mohammadi, H. Khabbaz, K. Vessalas, Enhancing mechanical performance of rubberised concrete pavements with sodium hydroxide treatment, Materials and Structures (2015) 1-15.
[10] H. Su, J. Yang, G.S. Ghataora, S. Dirar, Surface modified used rubber tyre aggregates: effect on recycled concrete performance, Magazine of Concrete Research 67(12) (2015) 680-691.
[11] D.M. Hamza, R.H. Ghedan, Effect Of Rubber Treatment On Compressive Strength And Thermal Conductivity Of Modified Rubberized Concrete, Journal of Engineering and Development 15(4) (2011) 21-29.
[12] S. Raffoul, R. Garcia, K. Pilakoutas, M. Guadagnini, N.F. Medina, Optimisation of rubberised concrete with high rubber content: an experimental investigation, Construction and Building Materials 124 (2016) 391-404.

[13] N. Deshpande, S.S. Kulkarni, T. Pawar, V. Gunde, Experimental investigation on strength characteristics of concrete using tyre rubber as aggregates in concrete, International Journal of Applied Engineering Research and Development 4(2) (2014) 97-108.
[14] A. Turatsinze, S. Bonnet, J.-L. Granju, Potential of rubber aggregates to modify properties of cement based-mortars: improvement in cracking shrinkage resistance, Construction and Building Materials 21(1) (2007) 176-181.
[15] M. Elchalakani, High strength rubberized concrete containing silica fume for the construction of sustainable road side barriers, Structures 1(0) (2015) 20-38.
[16] O. Youssf, R. Hassanli, J.E. Mills, M. Abd Elrahman, An experimental investigation of the mechanical performance and structural application of LECA-Rubcrete, Construction and Building Materials 175 (2018) 239-253.
[17] M.M. Al-Tayeb, B.H. Abu Bakar, H. Ismail, H.M. Akil, Effect of partial replacement of sand by recycled fine crumb rubber on the performance of hybrid rubberized-normal concrete under impact load: experiment and simulation, Journal of Cleaner Production 59(0) (2013) 284-289.
[18] O. Youssf, M.A. ElGawady, J.E. Mills, Experimental investigation of crumb rubber concrete columns under seismic loading, Structures, Elsevier, 2015, pp. 13-27.
[19] E. Eltayeb, X. Ma, Y. Zhuge, O. Youssf, J.E. Mills, Influence of rubber particles on the properties of foam concrete, Journal of Building Engineering 30 (2020) 101217.
[20] R. Hassanli, O. Youssf, J.E. Mills, Seismic Performance of Precast Posttensioned Segmental FRP-Confined and Unconfined Crumb Rubber Concrete Columns, Journal of Composites for Construction 21(4) (2017) 04017006.
[21] R. Hassanli, O. Youssf, J.E. Mills, R. Karim, T. Vincent, Performance of segmental self-centering rubberized concrete columns under different loading directions, Journal of Building Engineering 20 (2018) 285-302.
[22] R. Hassanli, O. Youssf, J.E. Mills, Experimental investigations of reinforced rubberized concrete structural members, Journal of Building Engineering 10 (2017) 149-165.
[23] O. Youssf, R. Hassanli, J.E. Mills, Retrofitting square columns using FRP-confined crumb rubber concrete to improve confinement efficiency, Construction and Building Materials 153(Supplement C) (2017) 146-156.
[24] M. Balaha, A. Badawy, M. Hashish, Effect of using ground waste tire rubber as fine aggregate on the behaviour of concrete mixes, Indian Journal of Engineering and Materials Sciences 14(6) (2007) 427.
[25] O. Youssf, M.A. ElGawady, J.E. Mills, X. Ma, An experimental investigation of crumb rubber concrete confined by fibre reinforced polymer tubes, Construction and Building Materials 53(0) (2014) 522-532.
[26] N.N. Eldin, A.B. Senouci, Rubber-tire particles as concrete aggregate, Journal of materials in civil engineering 5(4) (1993) 478-496.
[27] F. Pelisser, N. Zavarise, T.A. Longo, A.M. Bernardin, Concrete made with recycled tire rubber: Effect of alkaline activation and silica fume addition, Journal of Cleaner Production 19(6) (2011) 757-763.
[28] E. Güneyisi, M. Gesoğlu, T. Özturan, Properties of rubberized concretes containing silica fume, Cement and concrete research 34(12) (2004) 2309-2317.
[29] E.-S. Abd-Elaal, S. Araby, J.E. Mills, O. Youssf, R. Roychand, X. Ma, Y. Zhuge, R.J. Gravina, Novel approach to improve crumb rubber concrete strength using thermal treatment, Construction and Building Materials 229 (2019) 116901.
[30] S. Tian, T. Zhang, Y. Li, Research on Modifier and Modified Process for Rubber-Particle Used in Rubberized Concrete for Road, Advanced Materials Research 243 - 249(0) (2011) 4125-4130.
[31] G. Li, M.A. Stubblefield, G. Garrick, J. Eggers, C. Abadie, B. Huang, Development of waste tire modified concrete, Cement and concrete research 34(12) (2004) 2283-2289.
[32] C. Albano, N. Camacho, J. Reyes, J.L. Feliu, M. Hernández, Influence of scrap rubber addition to Portland I concrete composites: Destructive and non-destructive testing, Composite Structures 71(3–4) (2005) 439-446.
[33] B. Huang, X. Shu, J. Cao, A two-staged surface treatment to improve properties of rubber modified cement composites, Construction and Building Materials 40 (2013) 270-274.
[34] Q. Dong, B. Huang, X. Shu, Rubber modified concrete improved by chemically active coating and silane coupling agent, Construction and Building Materials 48(0) (2013) 116-123.
[35] G. Xiong, B. Luo, X. Wu, G. Li, L. Chen, Influence of silane coupling agent on quality of interfacial transition zone between concrete substrate and repair materials, Cement and Concrete Composites 28(1) (2006) 97-101.
[36] A.I. Abdulla, S.H. Ahmed, Effect of Rubber Treated by Acidic Solution on Some Mechanical Properties of Rubberize Cement Mortar, Eng. Technol. J. 29(13) (2011).

[37] J.O. Akinyele, R.W. Salim, W.K. Kupolati, The impact of rubber crumb on the mechanical and chemical properties of concrete, Engineering Structures and Technologies 7(4) (2015) 197-204.
[38] L. He, Y. Ma, Q. Liu, Y. Mu, Surface modification of crumb rubber and its influence on the mechanical properties of rubber-cement concrete, Construction and Building Materials 120 (2016) 403-407.
[39] A.M. Neville, Properties of Concrete Book 5th edition (1996).
[40] Standards Australia, Methods for testing concrete, Determination of air content of freshly mixed concrete - Measuring reduction in concrete volume with increased air pressure, AS 1012.4.1, 2014.
[41] E. Ganjian, M. Khorami, A.A. Maghsoudi, Scrap-tyre-rubber replacement for aggregate and filler in concrete, Construction and building materials 23(5) (2009) 1828-1836.
[42] Z.P. Bažant, A.B. Hauggaard, S. Baweja, F.-J. Ulm, Microprestress-solidification theory for concrete creep. I: Aging and drying effects, Journal of Engineering Mechanics 123(11) (1997) 1188-1194.
[43] M. Adamu, B.S. Mohammed, M.S. Liew, EFFECT OF CRUMB RUBBER AND NANO SILICA ON THE CREEP AND DRYING SHRINKAGE OF ROLLER COMPACTED CONCRETE PAVEMENT, International Journal 15(47) (2018) 58-65.
[44] Standards Australia, Methods of testing concrete - Determination of creep of concrete cylinders in compression, AS 1012.16, 1996.
[45] F.P. Torgal, Y. Ding, S. Jalali, Properties and durability of concrete containing polymeric wastes (tyre rubber and polyethylene terephthalate bottles): an overview, (2012).