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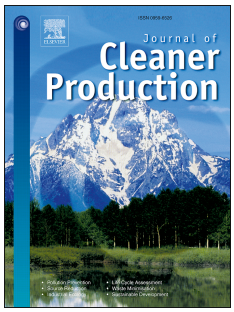

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Properties of concrete prepared with waste tyre rubber particles of uniform and varying sizes

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Abstract

Investigations and research into the recent use of rubber particles in concrete has been well documented. However, information on the rubber particle sizes or their distributions within concrete which may also influence the concrete properties is still limited. In this study, three groups of singly-sized rubber particle samples (3 mm, 0.5 mm and 0.3 mm) and one sample of continuous size grading (prepared by blending the three singly-sized samples to form the same particle distribution curve of sand) were used to replace 20% of the natural fine aggregate by volume. The reference concrete containing 100% sand was also prepared to

compare its properties with those of the samples in terms of workability, fresh density, compressive strength, tensile splitting strength, flexural strength and water permeability. The experimental results demonstrated that the rubber particle size affects the concrete mixture's workability and water permeability to a greater extent than the fresh density and strength. Concrete with rubber particles of larger size tends to have a higher workability and fresh density than that with smaller particle sizes. However, the rubber aggregates with smaller or continuously graded particle sizes are shown to have higher strengths and lower water permeability.

Keywords: Particle size distribution, rubber particles, concrete, workability, strength, water permeability

Abbreviations

BS	British standard
CCSR20	concrete with combined-size rubber, 20% fine aggregate by volume
CRA20	concrete with rubber sample A, 20% fine aggregate by volume
CRB20	concrete with rubber sample B, 20% fine aggregate by volume
CRC20	concrete with rubber sample C, 20% fine aggregate by volume
CSR	combined-sized rubber
EN	European norm
PSD	Particle size distribution
RA	rubber sample A
RB	rubber sample B
RC	rubber sample C
REF	reference mix without rubber
SSD	saturated surface dry

Variables in formulae

m_{ec}	mass of empty container
m_{fc}	mass of filled container
m_{OD}	mass of oven dried aggregate
m_{SSD}	mass of saturated surface dried aggregate
v_c	volume of container
v_{SSD}	volume of saturated surface dried aggregate

1. Introduction

Waste tyres have presented a pressing global issue for the environment, as a result of a growing use of road transport vehicles. Discarded waste tyres often create 'black pollution' because they are not readily biodegradable and pose a potential threat to the environment (Nehdi and Khan, 2001). Several means of reusing or recycling tyre rubber have been proposed, including the use of lightweight fill in the asphalt pavement, fuel for cement kilns, the feedstock for making carbon black, and the artificial reefs in marine environments (Prasad et al., 2009; Raghavan et al., 1998). However, some of these proposals are economically or environmentally unviable.

In the past twenty years, many attempts have been made to utilise recycled waste tyre rubber as an aggregate substitute in concrete. Together with other recycled aggregates, such as recycled concrete (Marie and Quiasrawi, 2012; Yang et al., 2011), and recycled glass (Ling and Poon, 2014; Castro and Brito, 2013), the recycling of scrap tyres has become a viable option for sustainable construction. A great number of applications have been reported on the use of waste rubber aggregate since an early study by Eldin and Senouci (1993). Most researchers have confirmed that there is a decrease in compressive strength and an increase in ductility with an increasing proportion of rubber phase in the mixture (Bignozzi and Sandrolini, 2006). To the authors' best knowledge, limited research work studies the effect of the size of rubber particles on the properties of resulting concrete, such as workability, strength and durability, as indicated by the literature review (Albano et al., 2005; Ali et al., 1993; Eldin and Senouci, 1993; Fattuhi and Clark, 1996; Li et al., 2009; Topçu, 1995). Furthermore, the conclusions from the reported studies are quite inconclusive due to the wide variations in the reported results.

In an early study, Eldin and Senouci (1993) reported that there was around 85% reduction in compressive strength and a 50% reduction in tensile strength when the coarse aggregates were fully replaced by coarse rubber chips. On the other hand, when fine aggregates were fully replaced by fine rubber, specimens lost up to 65% and 50% of their compressive strength and tensile strength respectively. Topçu (1995) reported the decrease of about 50% in the cylinder and cube compressive strength, and of 64% in the tensile strength observed in the concrete mixed with fine rubber particles. Introducing coarse rubber particles reduced the cylinder and cube compressive strengths by nearly 60% and 80%, respectively and the tensile strength by nearly 74%. These results indicate that the coarse rubber aggregates have a more significant negative effect than the fine rubber aggregates. However, the results of tests carried out by Fattuhi and Clark (1996) indicated the opposite trend. They found that adding fine graded rubber granules lowered the compressive strength of concrete more than the coarser graded granules. This was in agreement with Ali et al. (1993), but not with the findings of Eldin and Senouci (1993) or Topçu (1995).

In a recent study, Li et al. (2009) reported that using rubber particle sizes between 0.25 and 1 mm has less effect on the tensile splitting strength than on the compressive strength, and finer rubber was particularly beneficial for reducing the tensile splitting strength loss. These results partially disagree with the findings of Albano et al. (2005) who found that a decrease in the rubber particle size from 0.59 mm to 0.29 mm resulted in a lower workability and density at the fresh stage, as well as the weaker compressive and tensile splitting strengths at the dry stage. It is difficult to directly compare the results from various resources, as the nature of the raw materials, the test specimens and test methods were different. Hence, there remains a need to carry out further studies.

The aim of this study is to further the understanding of the effects of rubber particle size on the properties of the resulting concrete. To this end, three types of rubber particle samples with singly-sized rubber particles, and a fourth with rubber particles of varying sizes were used as part of the fine aggregate in concrete. A series of tests, including workability and density at the fresh stage, the cube compressive strength, the tensile splitting strength, the flexural strength and water permeability at the hardened stage were conducted according to relevant standards. Test results were analyzed and discussed, leading to the conclusions informing the tyre recycling industry to rationally design the particle size distribution (PSD) of rubber particles as the recycled aggregates.

2. Preparation of concrete

2.1. Materials

The materials used for preparing the test specimens comprised cement, water, coarse aggregate, fine aggregate and different sizes of rubber particles.

2.1.1 Cement

Ordinary Portland cement with a characteristic strength of 42.5 MPa was used in accordance with BS EN 197-1. This cement contains 30% of pulverised fuel ash which was taken into account in the mix design process. It was stored in airtight packages before use.

2.1.2 Water

Tap water that is reasonably free from contamination in the laboratory was used to hydrate the cement in the mixtures.

2.1.3 Coarse aggregate

Crushed gravels with a nominal maximum size of 10 mm were used as the coarse aggregate. Water absorption of the coarse aggregates used in this study under SSD condition was measured by immersion in water for 24 hours, followed by removing excess surface water with wet cloth after they were moved out of water. At the time when there was no free water on the surface, aggregates were assumed to be under the SSD condition. The sampled aggregates with saturated water under surface-dried condition were weighed and recorded as m_{SSD}. After 24 hours oven-drying the aggregates at a temperature of 105ºC, the aggregates were weighed and recorded as m_{OD}. The SSD water absorption was calculated by the formula of $(m_{SSD} - m_{OD})/m_{OD}$. The volume of the sampled aggregates under the SSD condition was measured by using water displacement method and recorded as v_{SSD}. The SSD density of gravels was calculated by the formula of m_{SSD}/v_{SSD}. Results of SSD water absorption and SSD density of gravels are presented in Table 1.

2.1.4 Fine aggregate

Natural river sand with a maximum particle size of 5 mm was used as the fine aggregate. Procedures for the sand SSD water absorption and SSD density measurements were the same as those for gravels, and the results are presented in Table 1. A sieve analysis test was carried out in accordance with BS EN 933-1. As shown in Fig. 1, the sand used in this study presented continuous granularity.

2.1.5 Rubber

Three different granular samples of waste tyre rubber particles, RA (cut to 3 mm), RB (grounded to 0.5 mm) and RC (grounded to 0.3 mm) without any treatment or contaminants, sourced from a local recycling plant, were used to replace part of the fine aggregate. CSR with continuous grading was achieved by blending RA, RB and RC manually. Sieve analysis

tests were carried out and the grading curve of each sample is shown in Fig. 1. RA, RB and RC were of relatively singly-sized, while the PSD of CSR was similar to sand with varying sizes.

SSD water absorption and SSD density of rubber particles were also measured. However, rubber particles were found to float in water. To overcome this problem, a tightly woven fabric was used to wrap rubber particles. The wrapped rubber particles were submerged in a water filled bucket, followed by gently shaking within the water to release as much trapped air as possible until it easily sank to the bottom of the bucket. Other procedures for measurements are the same as those for measuring coarse and fine aggregates. Results of SSD water absorption and SSD density of rubber particles are shown in Table 1.

2.2 Mix design

Concrete mix design was undertaken by using the method documented in the 'Design of Normal Concrete Mixes' (Teychenné et al., 1997) published by the Building Research Establishment. This design method is based on the determination of the material proportions.

The mix design of the reference concrete in this paper aimed to achieve a target mean strength of 53 MPa (often referred to grade C40/50) at 28 days with a slump value of 60-180 mm. A w/c ratio of 0.37 was determined according to target mean strength, cement strength class and type of aggregates. The amount of free water used to achieve the designed w/c ratio was determined according to the desired slump, the maximum size and the type of aggregate. Cement content was calculated by the values of w/c ratio and the amount of free water. Different sizes of rubber aggregates were used to replace 20% of the fine aggregates by

volume. The amount of coarse, fine and rubber aggregates of each concrete mixture were calculated.

Five concrete mixtures were produced to study the effect of rubber particle sizes and their distribution: REF, CRA20, CRB20, CRC20 and CCSR20. All mix design parameters were kept constant throughout the experiment programme except for the fine aggregate constituent. The mixture proportions are presented in Table 2.

2.3 Preparation of test specimens

2.3.1 Mixing

All types of aggregates were prepared to the SSD condition before mixing. The desired quantities of each item was accurately measured out and added in the following order: coarse aggregate, fine aggregate, cement and rubber aggregate in a mechanical mixer which had been inter-surface wetted. Prior to the addition of water, the mixer was turned on and the materials were blended for 5 minutes to achieve a though mix. Then half of water was added into the mixer for another 5 minutes blending. It was then repeated following the other half of water was added. The mechanical mixer was stopped when the mixture of ingredients appeared consistent.

2.3.2 Sampling

The mould shape and dimensions were: 100 mm cube, cylinder 100 mm in diameter and 200 mm in length, and 100 × 100 × 500 mm prism. Prior to pouring, the inner surfaces of the moulds were coated with a thin film of oil to prevent the concrete from adhering to the mould. All moulds were filled with fresh concrete in two equal layers, each of which was compacted using the vibrating table to remove as much air as possible. Vibration was continued for 30

seconds to ensure a smooth and even surface film, followed by trowelling the exposed surface to a clean finish.

2.3.3 Curing

Polythene sheeting was placed over the samples after casting to prevent moisture loss. After 24 hours at the ambient laboratory temperature of 20°C, the samples were carefully removed from the moulds, labelled with their IDs. The samples were then transferred to the water tank with a temperature of 20°C, where they will cure for sufficient time.

3. Experimental tests and results discussion

3.1. Workability

To evaluate the workability of fresh concrete, the slump was measured according to BS EN 12350-2. The slump cone and base plate were dampened before being placed on a horizontal surface. The mould was filled with a fresh concrete mixture in three layers, each approximately one-third of the height of the mould when compacted. Each layer was compacted with 25 strokes of the tamping rod. After the top layer was compacted, the surface of the fresh concrete was struck off by means of a sawing and rolling motion with the compacting rod. Then the mould was removed from the concrete by a steady upward lift in a vertical direction with no lateral or torsional motion being imparted to the concrete. Immediately after the removal of the slump cone, the slump was measured and recorded by determining the difference between the height of the mould and that of the highest point of the slumped test mixture (Fig. 2).

All the concrete mixtures were observed by visual inspection to be cohesive with no segregation or bleeding during the mixing, placing or compaction. Fig. 3 shows the slump

values obtained for all the concrete mixtures with and without the inclusion of rubber particles. The highest slump value of 95 mm was recorded for REF. The CRA20, CRB20, CRC20 and CCSR20 mixtures had slump values of 16.8% (16 mm), 23.2% (22 mm), 25.2% (24 mm) and 13.7% (13 mm) lower than that of REF. It can be implied from this result that there was a general reduction in slump values when rubber particles were used to replace sand, regardless of their particle size. This is mainly ascribed to the higher water absorption by the rubber particles compared to that of sand (see Table 1), which reduces the free water, thus making the overall concrete mixture less workable.

Also, it was observed that there was a decrease in slump as the rubber particle size was decreased. The slump of CRA20 with the largest rubber particle size was recorded as 79 mm. When the rubber particle size decreased from 3 mm (RA) to 0.5 mm (RB), the slump of CRB20 was 73 mm. When the rubber particle size was further reduced to 0.3 mm (RC), the slump of CRC20 continued to drop to 71 mm, which is the lowest of all the samples. This is due to the higher surface area and water absorbability of the finer rubber particles. From Table 1, it can be seen that the SSD water absorption of the finer rubber particles, RB and RC, are 10.70% and 10.09%, which is higher than the larger rubber particles RA (4.49%). This means that during the mixing, the finer rubber particles will absorb more free water than the larger rubber particles to achieve the SSD condition. Therefore, the slump of CRB20 and CRC20 with less free water is lower than that of CRA20. Another reason may be that the surface of the finer rubber particle is rougher than the larger one. During the waste tyre treatment process, tyres are cut into small pieces before being thrown into a cracker grinding mill. The grinding process is then carried out for a certain length of time before the different sized rubber particles are sieved and packed. Fig. 4 shows the surface of the different sized rubber particles. It can be seen clearly that there are some dents and jagged areas on the

surfaces of the RB and RC samples. The surface of RA is much smoother than that of RB and RC. Moreover, the larger surface area of the finer particles produces more frictional resistance to the flowing movement of fresh concrete. Fig. 3 also shows that the drop of slump for the CCSR20 mixture (13 mm) is lower than those of the other rubber concrete samples. This is due to the fact that the grading of the rubber particles affects the packing density of aggregates. The cement paste required to fill in the voids in the aggregate skeleton is reduced for the better packed aggregates and hence more cement paste can provide lubrication and hence increase the workability. In this case, the combined rubber particles (CCSR20) have a better packing density than those singly-sized samples, and hence show a better workability. Aggregates that do not have a large deficiency or excess of any particular size produce the most workable and economical concrete mixtures (Mehta and Monteiro, 2013).

3.2. Fresh density

The density test for fresh concrete was carried out in accordance with BS EN 12350-6. A container of known volume v_c was weighed to determine its mass and the value was recorded as m_{ce}. The container was then filled with fresh concrete in two layers, each approximately half of the height of the container. Each layer was then compacted immediately after placing it in the container by applying vibration from a vibrating table for the minimum duration necessary to achieve full compaction of the concrete with neither excessive segregation nor laitance. After the top layer was compacted, the surface was skimmed to be smooth using a trowel and the outside of the container was wiped clean. The container with its contents was re-weighed to determine its mass and the value was recorded as m_{cf}. The fresh density was calculated using the formula of $(m_{cf} - m_{ce})/v_c$.

The fresh density test results for all the samples are shown in Fig. 5. Irrespective of the rubber particle size used, a clear reduction in the concrete fresh density was observed with the incorporation of rubber aggregates. This is mainly due to the differences in the density of rubber aggregates. However, the rubber particles with different sizes have resulted in differing reductions in the concrete fresh density. The percentage decrease in density for CRA20, CRB20, CRC20 and CCSR20 were 3.1%, 3.9%, 3.8%, and 3.5%, as compared to REF. The reduction in the fresh density of the concrete with the RA aggregate was the smallest, while the CSR, RB and RC aggregates showed a slightly higher level of reduction. This is in agreement with the original density values of the rubber aggregates, where RA possesses a relatively higher density (1,111 kg/m^3) than CSR (973 kg/m^3), RB and RC (909 kg/m^3). A similar observation on the density of rubber concrete was reported by Siddique and Naik (2004). They suggested that the non-polar nature of rubber particles may result in the ability to repel water and entrap air on the rubber surface, which would subsequently increase the number of air voids and thus decrease the concrete density. As the rubber content was limited to 20% in this study, the extent of differences among the concrete mixes was not significant.

3.3. Compressive strength

The 28 days compressive strength of hardened concrete was tested according to BS EN 12390-3. The excess moisture from the surface of the cube specimen was wiped before testing. The specimen was then positioned at the centre of the loading plate in a Denison testing machine, with two non-trowelled surfaces contacted with the load platens so that a uniform loading can be achieved. Once the test was started, uniaxial compression was applied continuously at a constant rate of 0.6 MPa/s. When the sample failed, the value indicated was recorded, and the mean of three samples was taken as the final result.

Replacing natural river sand with relatively soft rubber aggregate is expected to reduce the concrete compressive strength. This was confirmed by the test results of the 28 days cube compressive strength test results, as shown in Fig. 6. The compressive strength of CRA20, CRB20, CRC20 and CCSR20 decreased by approximately 10.6%, 9.6%, 9.5% and 9.8% as compared to that of the REF (61.1 MPa). This can be attributed to the low stiffness and poor surface texture of the rubber particles that resulted in an inconsistency of the concrete mix, and the lack of bonding between the rubber particles and the surrounding cement paste, leading to a loss of compressive strength (Eldin and Senouci, 1993). A similar decrease in strength with the use of rubber particles in concrete was reported by Guo et al. (2014) and Li et al. (2004). However, all the rubber concretes investigated in this study had a compressive strength higher than the target mean strength of 53 MPa.

Fig. 6 shows that the 28 day cube compressive strengths of CRA20, CRB20 and CRC20 were 54.6 MPa, 55.2 MPa and 55.3 MPa. This indicates that the compressive strength of the concrete increased modestly with a decrease in the rubber particle size. This is because the finer rubber particles have a better voids-filling ability, resulting in low void space and leading to higher compressive strength. Also, because the failure of concrete samples is primarily caused by debonding between the aggregates and the cement paste, the bond plays a significant role in determining the concrete strength. As reported in Section 3.1, RA presents a smoother surface than RB or RC, which results into a weaker bond between the rubber aggregates and the surrounding cement paste. To support this argument, a series of microscopic inspections of the crushed samples were carried out using scanning optical microscopy. The rubber-matrix interfaces were inspected in 10 crushed concrete particles from each sample. To demonstrate the difference in the interfacial behaviour, the

micrographs of the fracture surfaces of CRA20 and CRC20 are presented in Fig. 7. As shown in Figs. 7a and 7b, a clear discontinuity can be found along boundary lines I and II. There is a distinct groove along line II, which indicates that the adhesion between the rubber particle and the concrete matrix is poor, leading to a lower compressive strength of CRA20. In contrast, in the micrograph of CRC20 (see Fig. 7c), a well-developed adhesive interfacial zone is observed between the fine rubber particle and the concrete matrix. From its 3D image shown in Fig. 7d, it can be seen that the transition zone between the rubber particle and the concrete matrix is smooth; whereas for CRA20 a clear trough can be observed along line II, as shown in Fig. 7b. This observation suggests that there is a relatively stronger bond at the interface between the finer rubber particles and the concrete matrix. Owing to the continuous grading, the CSR aggregate should have a filler effect to improve particle packing in concrete, thereby reducing the strength loss. However, the results shown in Fig. 6 reveal that CCSR20 gained a similar strength to those of CRB20 and CRC20, which was slightly higher than that of CRA20. This observation suggests that the negative effect of the rubber surface on the compressive strength overweighs the positive filler effect of PSD, but to a minor extent.

3.4. Tensile splitting and flexural strengths

Tests on the tensile splitting strength and the flexural strength of hardened concrete at 28 days after casting were conducted in conformity with BS EN 12390-6 and BS EN 12390-5, respectively. The excess moisture from the surface of the specimen was wiped before testing in a Denison strength testing machine. In the tensile splitting strength test, the concrete cylinder specimen was placed horizontally in a frame with two hardboard packing strips positioned along the top and bottom of the specimen between the metal plate and the concrete. Continuous loading was applied by a compression platen to a narrow region of the cylinder along its length at a constant rate of 0.05 MPa/s. When the sample failed, the loading value

was recorded and the mean of three samples was calculated. In measuring the flexural strength, the concrete beam specimen was positioned so that it would be simply supported on two lower rollers at a spacing of 300 mm. Continuous loading was applied by two upper rollers (at a spacing of 100 mm) to the centre of a non-trowelled specimen face at a constant rate of 0.05 MPa/s. When the sample failed, the loading value was recorded and the mean of three samples was calculated.

The results of the 28 days tensile splitting and flexural strengths tests are shown in Fig. 8. As in the case of compressive strength, the inclusion of rubber particles decreases both the tensile splitting and the flexural strengths. These results are in line with the work reported by Toutanji (1995) on the influence of rubber particles on the properties of concrete, which showed that there was a decrease of about 7.9% in the flexural strength with the inclusion of 25% rubber aggregate as the natural aggregate replacement. The current investigation shows that when 20% of the fine aggregate was substituted with the rubber aggregate, there was a decrease in flexural strength of approximately 12.8%, 11.3% and 10.9% for CRA20, CRB20 and CRC20. In a similar trend, there were reductions of 11.1%, 8.3% and 6.9% in the tensile-splitting strength for CRA20, CRB20 and CRC20. It can be further deduced that the smaller the size of the rubber particles, the less the strength loss. The reason for this is similar to that for the compressive strength, as the smaller rubber particles may have a filler effect to increase the compactness of the concrete, and to reduce the level of stress singularity arising at the internal voids, and consequently reduce the likelihood of fracture. This also explains the fact that the particle size has a greater effect on reducing the tensile splitting strength and the flexural strength than on the compressive strength. Tensile splitting and flexural strengths of 3.32 MPa and 6.14 MPa were recorded for CCSR20. It can be seen from these results that incorporating various sized rubber particles does not significantly affect the tensile splitting

and flexural strengths of concrete compared to singly-sized crumb rubber. In fact, the reduction effect for CCSR20 is between the bounds formed by the single rubber particle. Thus it can be inferred that incorporating well-graded rubber particles into the concrete does not affect the tensile splitting strength or the flexural strength significantly.

3.5. Water permeability

A water permeability test was performed using the Autoclam test equipment as shown in Fig. 9. This was performed as a modified version of BS 1881-208. 100 mm cube specimens were preconditioned (by being sheltered for one week) to remove as much moisture as possible before the water permeability test was undertaken. Prior to testing, it was ensured that the water reservoir was completely full. A metal ring with an internal diameter of 50 mm was attached (using an adhesive) to the surface of the specimen, and then the Autoclam was clamped onto the ring using bolts. The equipment was then switched on and the water was allowed to be drawn into the Autoclam. Finally, the cumulative flow of water into the concrete at a pressure of 500 mbar was recorded every minute for a duration of 15 minutes.

Fig. 10 shows the volume of water plotted against the square root of time according to the recommendations of The Concrete Society (2008). A regression equation for each specimen was determined, and the gradients of the lines between the 5^{th} and 15^{th} reading, which is known as the water permeability index, are shown in Table 3. Another two repeated testing on two separate samples were conducted and the mean of the results are shown in Fig. 11. It was found that the increase in the permeability index for CRA20, CRB20, CRC20 and CCSR20 were 3.09, 1.42, 1.39 and 1.25 times the permeability index of REF. This means that the water permeability resistance of concrete is generally weakened when rubber is incorporated. This observed behaviour is similar to that reported by other researchers (Bravo

and Brito, 2012; Ganjian et al., 2009; Bignozzi and Sandrolini, 2006). It can be directly attributed to the increased porosity of rubber concrete. Because the lightweight crumb rubber tends to float in the wet mixture, this, coupled with its elastic behaviour under the compact condition, leads to the poorly compacted concrete containing more voids (Onuaguluchi and Panesar, 2014).

Two observations can be made from the test results presented in this section. Firstly, water permeability decreases with a decrease in rubber particle size. This may be due to the fact that when sand is partly replaced by large rubber particles (3 mm in this study), the resulting concrete (CRA20) cannot be as dense as concretes containing smaller or well-graded rubber particles (CRB20, CRC20 and CCSR20), resulting in more micro-conduits for water to travel through. Secondly, the resistance to water permeability of the concrete with CSR aggregate is higher than those with RA, RB and RC aggregates. This phenomenon is attributable to the PSD of CSR. Aggregate grading has a considerable effect on the voids structure of a concrete mixture (Mehta and Monteiro, 2013). Rubber particles with different sizes make the concrete more compact because the finer rubber particles fill the gaps formed by the larger ones. As a result, the number of conduits through which the water can transport is reduced. In comparison with the established values of the water permeability index classification shown in Table 4, it was found that, except for CRA20, all other mixes attained a 'very good' protective quality. Of all the concrete samples with rubber, the index of CCSR20 is the lowest, with a value of 1.70×10^{-7} $m^3/\sqrt{min}$, which is less than the recommended value of 3.7×10^{-7} $m^3/\sqrt{min}$. Therefore, it can be concluded that CSR is preferred with respect to the performance of water permeability.

4. Conclusions and outlook

Workability, fresh density, compressive strength, tensile splitting strength, flexural strength and water permeability of concrete with different rubber particle sizes were studied and compared in this paper. From the results of the experimental study, the main conclusions can be summarised that using different sizes of rubber particles in concrete as part of the fine aggregates affects the workability and water permeability considerably more than the fresh density and concrete strengths. Concrete specimens prepared with the larger rubber particles show a better workability than those with finer ones. Conversely, concrete with the finer rubber particles has a better performance in strengths and water permeability than those with the larger rubber particles. Varying sized rubber aggregates with continuous grading offer better workability and resistance to water permeability compared to the singly-sized rubber particles. In terms of the strength of concrete, the varying sized rubber performed similar to the finer rubber particles in the tests when added to the concrete mix.

The findings of this paper can potentially be beneficial to the tyre recycling industry in designing the particle size distribution of rubber particles used for recycled aggregates. For example, rubber particles with well-graded sizes are preferred when high workability and water permeability resistance in rubber concrete are required. In engineering practice, the desired grading of rubber particles can be prepared at the waste tyre recycling and processing plant, which may save some time and capital cost. Furthermore, the dynamic performance of rubber concrete products is likely to be important. With a highly resilient nature, rubber particles of different sizes have a more positive effect on the dynamic performance when included in concrete. Research into the fatigue property and the ductility behaviour of concrete with rubber particles of combined sizes is currently in progress.

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List of Tables

Table 1: SSD density and SSD water absorption of natural and rubber aggregates

Item	Sand	Gravel	RA	RB	RC	CSR
SSD density (kg/m^3)	2512	2581	1111	909	909	973
SSD water absorption (%)	1.37	1.26	4.49	10.70	10.09	8.46

Table 2: Mix proportions of concrete

Notation	Water	Cement	Sand	Gravel	Rubber
REF	234	632	519	1013	0
CRA20	232	627	416	1005	46
CRB20	230	621	410	996	37
CRC20	230	621	410	996	37
CCSR20	232	627	414	1002	40

1. Unit: kg/m^3
2. The values of sand, gravel and rubber are under SSD condition

Table 3: Regression equations and index of water permeability of all the tested mixes

Samples	Regression equation	Water permeability index ($\times 10^{-7}$ m$^3/\sqrt{\text{min}}$)
REF	$y = 1.32 \times 10^{-7}\chi + 5.76 \times 10^{-7}$	1.32
CRA20	$y = 4.17 \times 10^{-7}\chi - 6.03 \times 10^{-7}$	4.17
CRB20	$y = 1.99 \times 10^{-7}\chi + 2.50 \times 10^{-7}$	1.99
CRC20	$y = 1.94 \times 10^{-7}\chi - 3.46 \times 10^{-7}$	1.94
CCSR20	$y = 1.77 \times 10^{-7}\chi - 9.43 \times 10^{-8}$	1.77

Table 4: Water permeability index of protective quality (The Concrete Society, 2008)

Protective quality	Water permeability index ($\times 10^{-7}$ m$^3/\sqrt{\text{min}}$)
Very good	≤3.70
Good	3.70 – 9.40
Poor	9.40 – 13.80
Very poor	>13.80

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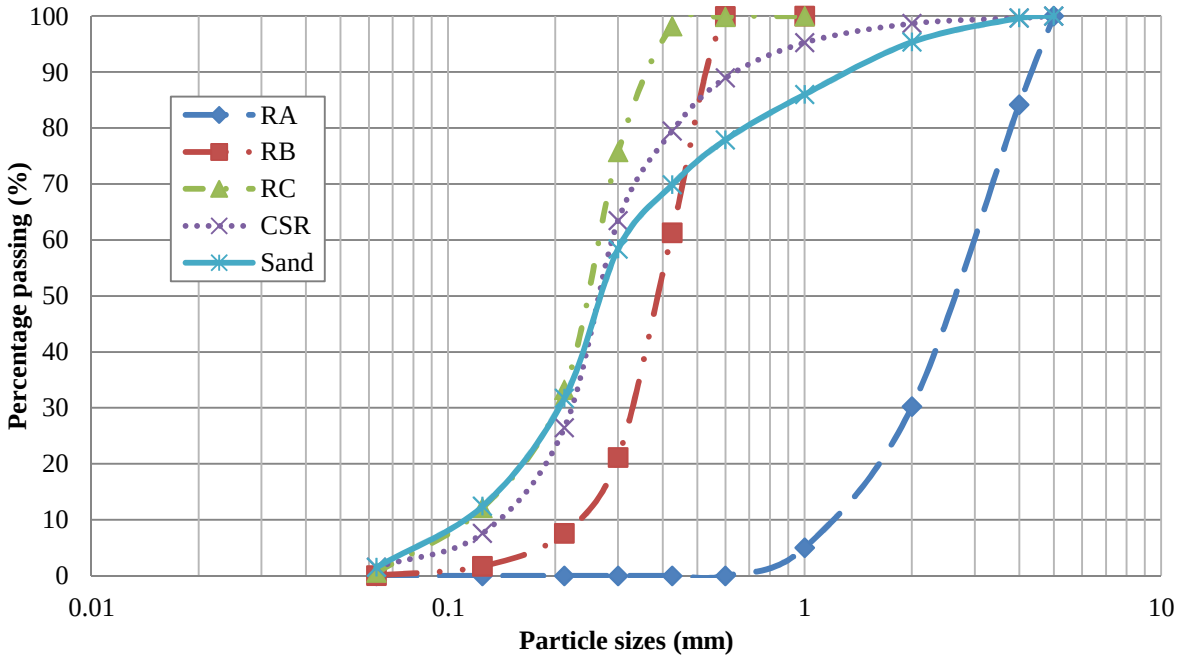


Fig. 1: Grading curves of sand and rubber particles

Fig. 2: Typical slumped test

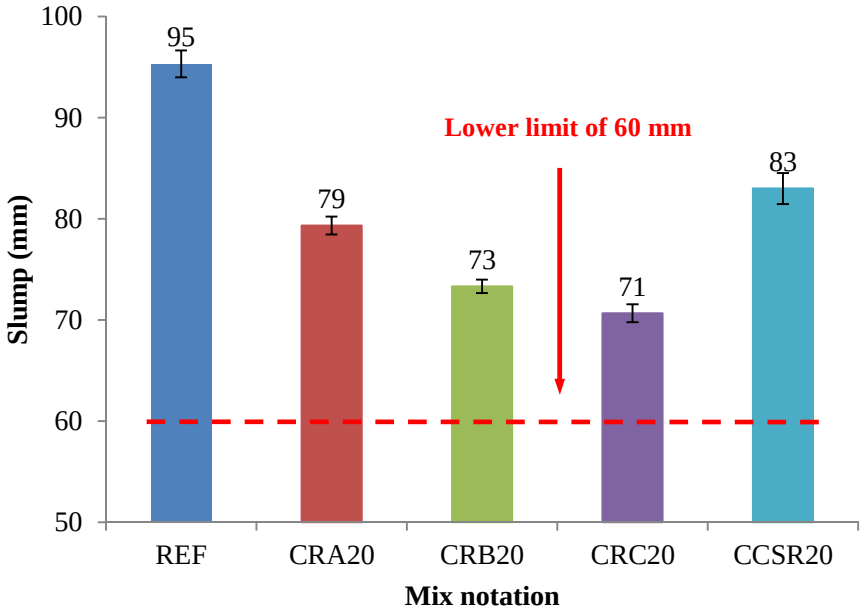
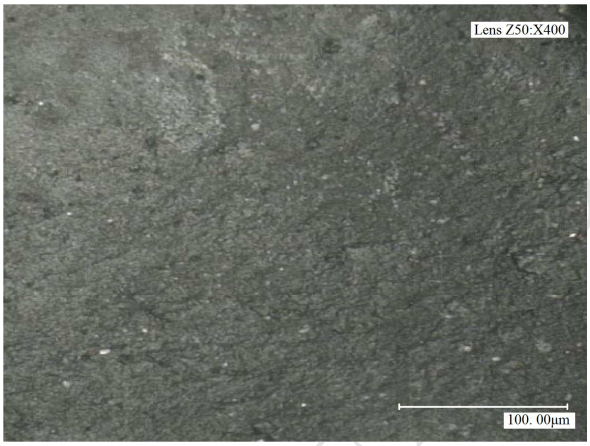
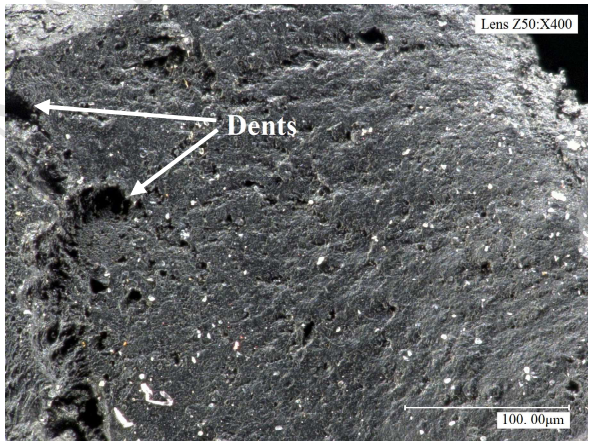


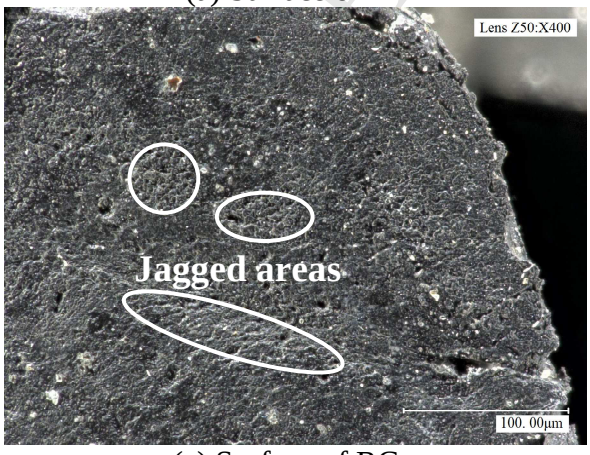
Fig. 3: Slump of all the mixes



(a) Surface of RA



(b) Surface of RB



(c) Surface of RC

Fig. 4: Surfaces of different sizes of rubber particles

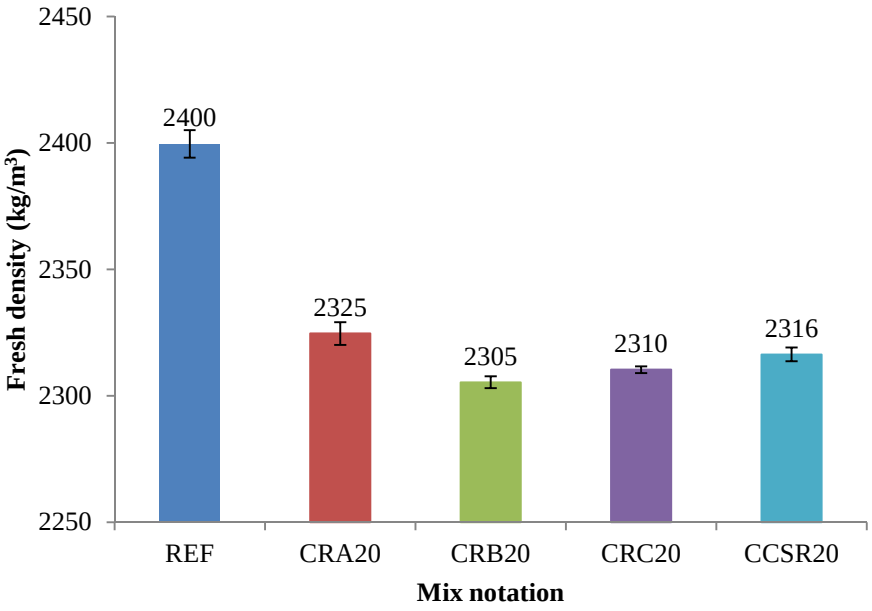


Fig. 5: Fresh density of all the mixes

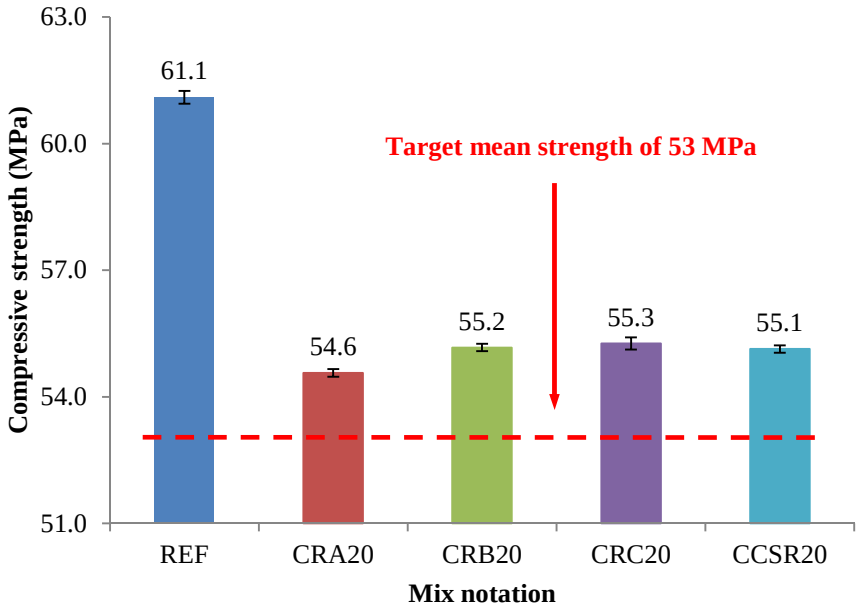
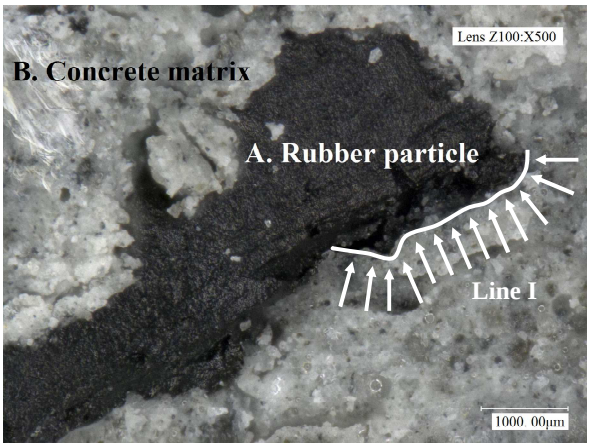
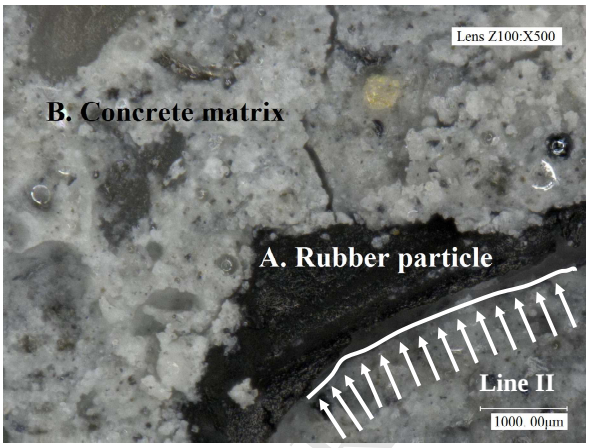


Fig. 6: 28 days compressive strength of all the mixes

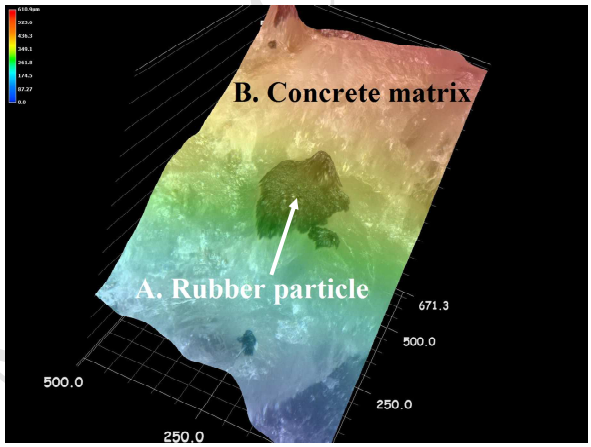


(a) Rubber-matrix interface of CRA20 (I)



(b) Rubber-matrix interface of CRA20 (II)

(c) Rubber-matrix interface of CRC20



(d) 3D image of rubber-matrix interface of CRC20

Fig. 7: Micrographs of rubber-matrix interface

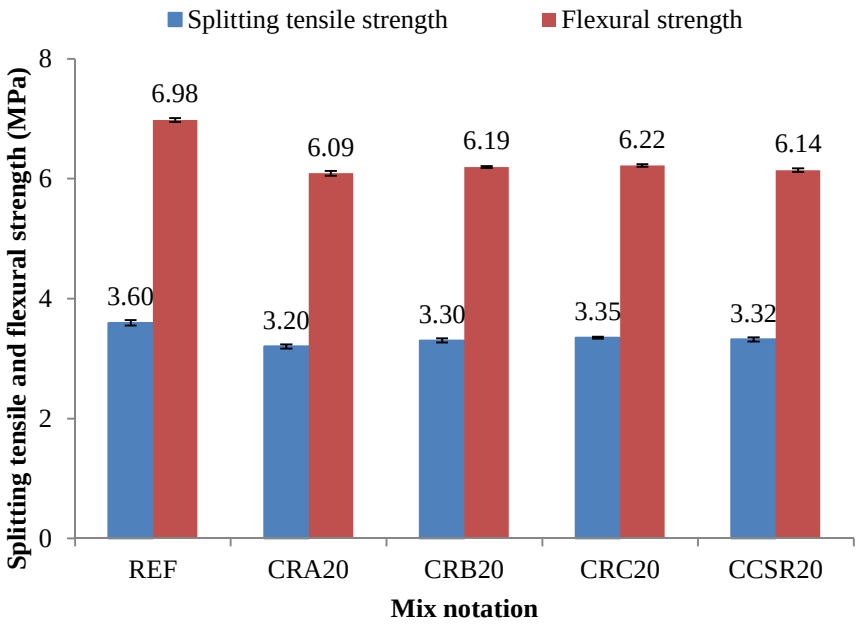


Fig. 8: 28 days tensile splitting and flexural strengths of all the mixes

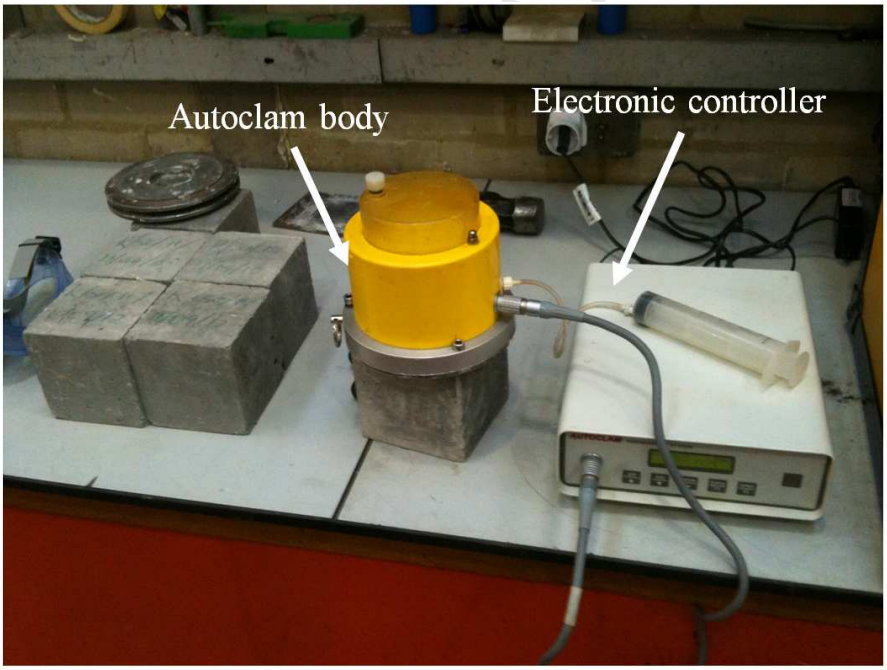


Fig. 9: Apparatus for water permeability test

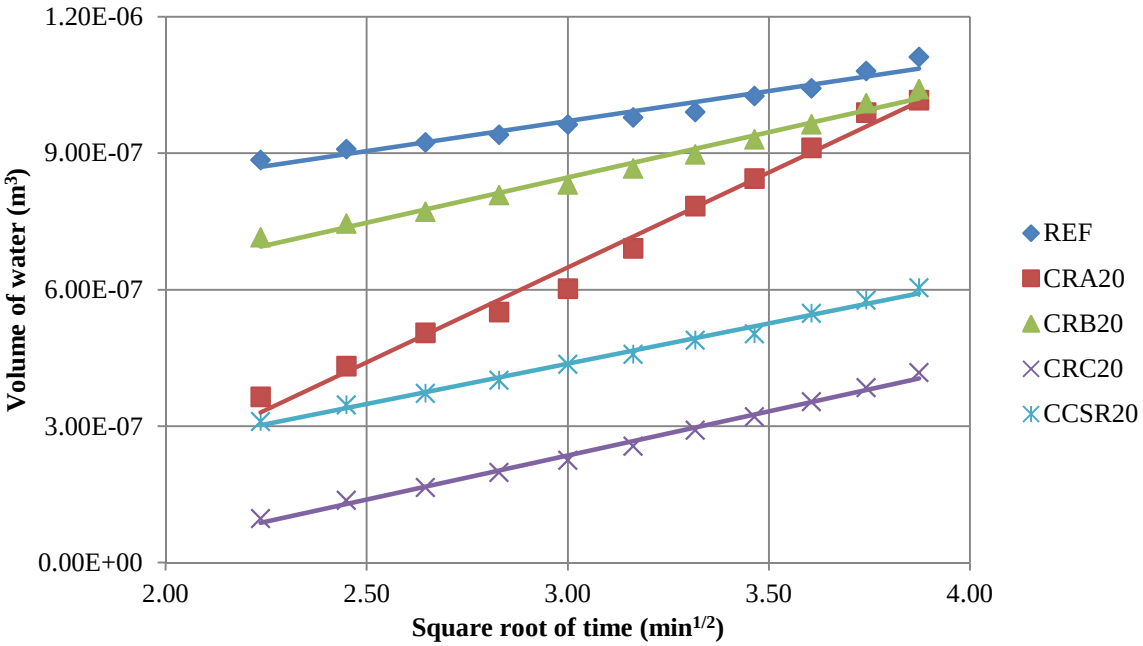


Fig. 10: Volume of water flowing into specimen with time

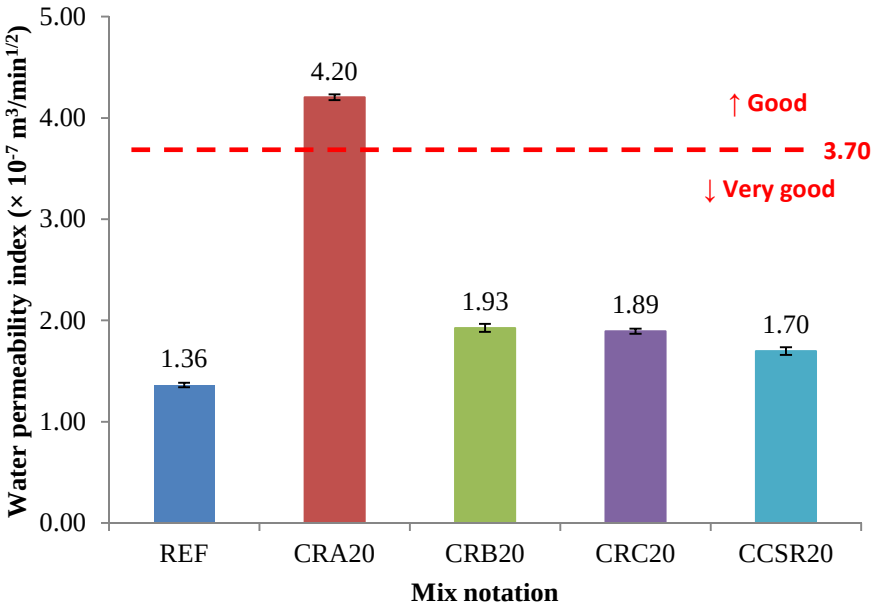


Fig. 11: Water permeability indices of all the mixes

Research highlights:

- Properties of concrete with different rubber sizes and distributions were studied.
- Rubber size affects the workability and water permeability more considerably.
- Concrete with large rubber particles shows a better workability than fine ones.
- Concrete with fine rubber particles has a higher strength and lower water permeability.
- Well graded rubber aggregates offer better workability and permeability resistance.