PERMEATION CHARACTERISTICS AND DURABILITY ASPECTS FOR SUSTAINABLE CONCRETE

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This study investigates the durability indicators for sustainable concrete produced by adding both crumbed rubber and steel fibres that are removed from waste tyres to the concrete mixes. Crumb rubber was treated by submersion in sodium hydroxide and then used to partially replace 10% and 30% of fine aggregates in the concrete mix. Extracted steel fibres were added at the rate of 1% and 2% per volume of each mix. The compressive strength was recorded, and a non-destructive air permeability test was used to assess permeation characteristics of studied specimens and to correlate the results with compressive strength results. It was found that with the increase in the steel fibres percentage while keeping the rubber content constant resulted in increased compressive strength of concrete. Rubberized concrete of 10% crumb rubber and 1% steel fibres exposed to oven drying at 105°C for 12 hours exhibited an increase in compressive strength. The addition of crumb rubber and steel fibres as a partial fine aggregate replacement resulted in increasing the air permeability of the concrete to different degrees depending on the percentages used. This study showed that waste tyres extracts can be a viable, economic, and environmentally friendly method for obtaining durable and sustainable concrete.

Keywords: concrete; waste tyres; steel fibres; durability aspects; air permeability; compressive strength

1. INTRODUCTION

As the potential to reproduce green sustainable concrete, researchers investigated the use of tyre waste in concrete for construction (Ibrahim and Razak, 2016; Adeboje et al., 2018-2020). The advantages gained by using waste tyres in concrete included minimizing the environmental impact, reducing the usage of natural aggregate–and reducing the space volume used for disposals in landfills. Sofi (2018) reported that using tyre waste as coarse or fine aggregate would adversely affect the mechanical properties as well as durability of the concrete because the interfacial zones between the rubber and cement may act as a micro-crack due to weak bonding between the two materials. However, Dobrotă1 and Paraschiv (2017) recommended in their study that good enhancement in physical and mechanical characteristics was achieved after thermal treatment of the rubber using an autoclave.

Aslani and Gedeon (2019) studied rubberized concrete containing 0.25% - 1% polypropylene, steel fibres and crumb rubber replacement of 20% of fine aggregate. The work reported that the addition of steel fibres from 0.75% led to improved tensile strength of overheated rubberized concrete having 10% crumb rubber compared to normal concrete. Abdullah et al., (2018) reported that the split tensile strength linearly decreased with rubber content above 6%. The strength then declined at further replacement rates for overheated specimens (200°C-600°C). These studies found that workability of fibre reinforced concrete was lower than that of normal concrete. Compressive, tensile, and flexural strengths were increased with the addition of fibre. Treatment of crumb rubber with sodium hydroxide (NaOH) solution has been widely used to increase the bond between cement and rubber resulting in increased strength (Liu and Zhang, 2015). Zukri et al., (2017) reported enhancement in the mechanical properties of the concrete when using treated rubber by sodium hydroxide.

The quality of concrete can be defined by its durability. The durability is usually presented by destructive and non-destructive properties that can be attained. The quality of concrete cover is considered the first line of defense for steel reinforcement against aggressive exposure to substance and environment (Dhir et al., 1993; Claisse et al., 1999a and b; 2003). Simple indicators such as in-situ permeation tests are reasonable and easy tools to measure the amount of fluid or air transmitted through the concrete surface and near surface (concrete cover).

Claisse et al., (2003) drilled three holes in their specimens, rather than a single hole as initially proposed for the Figg testing method, which resulted in repeatable and consistent results. Air permeability apparatus for laboratory and in-situ testing based on the vacuum technique was developed to overcome the disadvantages of handling and operation cost (Dhir et al., 1993; Dhir et al., 1995; Claisse et al., 1997; Claisse et al., 1999 b). The vacuum technique has been based on vacuum preconditioning and permeability by monitoring pressure decay in concrete cover (concrete near surface). Claisse et al. (1999b); Katapady et al., (2018) found that there were direct relationships between air permeability, pore volume, and durability aspects such as depth of carbonation, chloride diffusion, and the compressive strength results. It became apparent that the air permeability of concrete containing crumb rubber and waste steel fibres either preconditioned by drying in the oven or by drying at room temperature had not been investigated.

In this investigation, correlation between the mechanical properties and the air permeability of rubberized concrete including the steel fibre extracted from tyre wastes was assessed. A simple easy to use non-destructive portable air permeability apparatus was developed to measure concrete near surface air permeation successfully. The analysis of these experimental results will be able to advance the disposal of waste tyres and lead to a more sustainable, economical, and durable concrete for infrastructure and structural applications in construction.

2. EXPERIMENTAL PROGRAMME

In this study, five mixes were considered. The mixes contained specimens for oven dried curing (preconditioning) as well as normal curing. In addition to the tests to assess the compressive strength of the concrete, a non-destructive air permeability test was used to assess permeation characteristics of studied specimens and to correlate the results with compressive strength results. This also provided a simple method for detecting the quality of the rubberized concrete.

2.1 Materials

The design of the control mix (without crumb rubber and steel fibres) was carried out to achieve a target compressive strength of 30 MPa at 28 days in standard water curing. This target strength represents what has been considered here as a reasonable concrete strength for concrete applications. The maximum aggregate size was 20 mm. For comparison purposes, the water/cement ratio was constant for all mixes with a ratio value of 0.5. The different portions of concrete mix components to produce one cubic meter of concrete are listed in Table 1. The slump values ranged from 40 to 80 mm depending on the percentages of crumb rubber and steel fibres as indicated in Table 1. It can be observed from Table 1 that as the crumb rubber percentage increased, the slump increased. However, when the percentage of steel fibres was increased, the slump was reduced in mix, M10@2 but increased in mix M30@2.

Table 1 Material quantities for concrete mix

Mix designation	Solid constituents and proportions, kg/m^3					Water, Liter/ m^3	Water/ cement	Slump, mm
	Cement	Sand**	Crumb** rubber	Steel fibers	Coarse aggregates			
Control*	350	620	--	--	1230	175	0.50	40
M10@1	350	530	30	75	1230	175	0.50	55
M10@2	350	450	30	150	1230	175	0.50	50
M30@1	350	480	90	75	1230	175	0.50	75
M30@2	350	400	90	150	1230	175	0.50	80

*Target Strength, 30 MPa
** The replacement of sand with crumb rubber was by volume (the weights above are for 1m^3)

Crumb Rubber and Treatment

Pre-treatment of the rubber crumb was carried out in this research based on the recommendations of Liu and Zhang (2015); Zukri et al. (2017) by submerging crumb rubber for 30 minutes in "1 N NaOH" solution (one mole concentration of sodium hydroxide solution) at room temperature. After treatment with the NaOH solution, the rubber particles were washed with potable water for a period of 5 minutes until the pH of the washing water became neutral. The crumbs were then dried by a stream of warm air before adding to the concrete mixes.

Preparation of Steel Fibres

The steel fibres extracted from the waste tyres were cut into nominal lengths of 40 mm using a cut wire method. The fibres were extracted by magnetic separator after burning, similar to the method described by Rashid and Balouch (2017). The Steel fibres were corrugated with nominal lengths equal to 40 mm, a nominal diameter of 1.0 mm and aspect ratio of 40. Steel fibres were added to the mixes manually in the form of fine aggregate together with the crumb rubber according to ACI 544.1R (2002).

Cement

Masterceret UK provided the cement that met all the conformity criteria to BS EN 197-1 (2011).

Sand

The fine aggregate used can be classified as ordinary sand with a yellow and rough texture. The fineness modulus was measured by sieve analysis and found to be 2.7. The density was measured using a pycnometer: the cement density obtained was 2630 kg/m^3, while the natural bulk density of the sand was 1700 kg/m^3.

2.2 Samples Preparation

A total of five mixes were designed: a control mix and four sample mixes with two different percentages of crumb rubber (10% and 30%) and two different percentages of steel fibres (1% and 2%). The crumb rubber partially replaced fine aggregate and the steel fibres were added as a percentage of concrete volume. Thomas et et al., (2016) suggested that the relative specific gravities of the rubber crumb and sand must be considered during the mix design. Therefore, more rubber weight was added compared to the sand replaced. Quantities of materials used for mix design are reported in Table 1 for 1 m^3. The specimens were cast in the laboratory and left in their moulds for 24 hours at room temperature.

The procedure for mixing took place by firstly adding the dry coarse aggregate, sand, rubber, and steel fibres followed by the cement in that order. The water was lastly added and mixed continuously until a uniform matrix had been achieved.

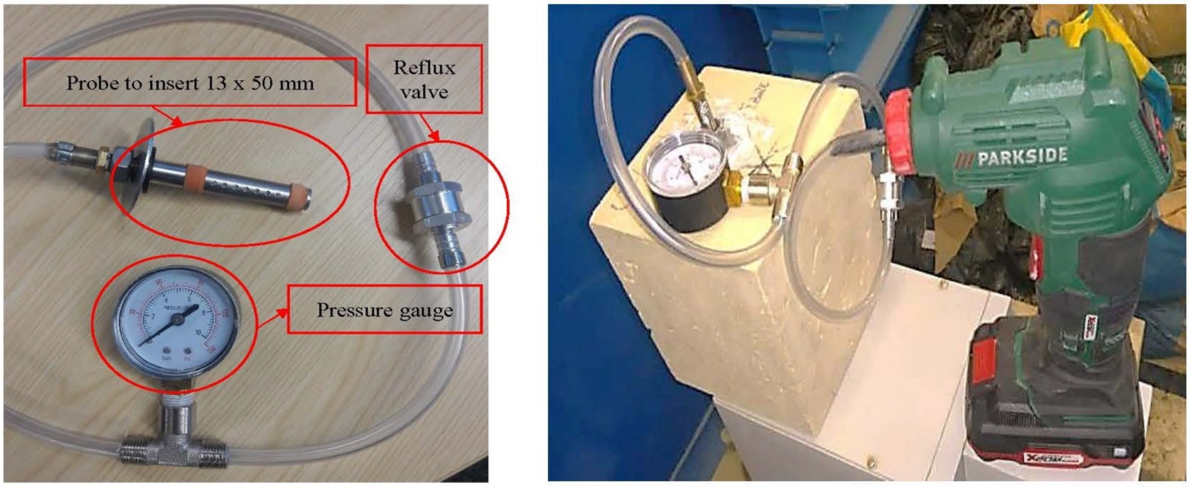
Concrete cube specimens of 150 x 150 x 150 mm were prepared. The specimens were cured in water for up to 28 days. For the samples preconditioned by drying in the oven, they were kept in the oven for 12 hours at 105ºC and then cooled in laboratory air before being tested for air permeability or mechanical properties. This time and temperature were chosen to avoid damage of the pore structure while drying (Dhir et al., 1995) and to obtain reliable results. The specimens were tested for compressive strength after two curing time periods: 7 and 28 days (3 samples were tested at each age for each mix and drying condition). The other specimens, which were not dried in the oven, were tested immediately after curing. After curing and or drying (preconditioning), selected cube specimens were drilled with holes of 13 mm diameter and depth of 50 mm in order to insert the probe for measuring the air permeability index (3 samples were tested for each mix and drying condition).

2.3 Test Methods

Concrete cube specimens were used to test the compressive strengths as well as air permeability assessment as described in 2.2.

2.3.1 Air Permeability Assessment

The air permeability of concrete cover was assessed using a non-destructive portable technique (Shaaban et al., 2021). Air permeability index was assessed based on measuring the pressure decay of compressed air by a portable air compressor to near surface concrete. A new steel probe was developed to obtain repeatable and consistent results. The full details of the apparatus and the whole process of running the test are explained elsewhere (Shaaban et al., 2021). The components of the portable air permeation test are shown in Figure 1 (a) and the test setup is shown in Figure 1 (b).



(a) Probe, pressure gauge, and reflux valve. (b) Test apparatus attached to a portable pump.

Figure 1: Developed portable permeability index test apparatus

3. EXPERIMENTAL RESULTS AND DISCUSSION

The concrete mixes were designed to include a partial replacement of the fine aggregate. Mechanical properties air permeability of concrete was measured using the portable non-destructive technique.

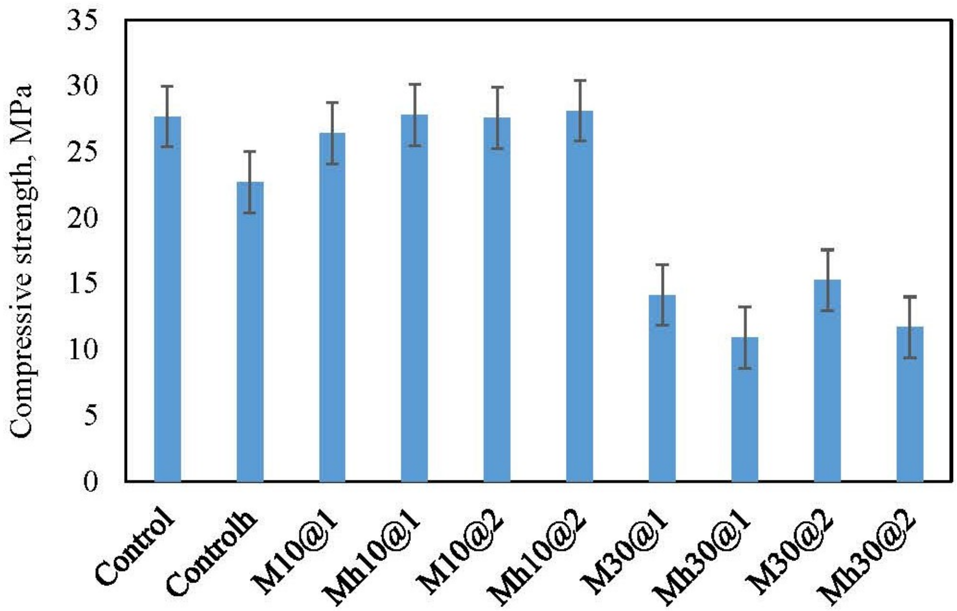
3.1 Compressive Strength

Results of the compressive strength test at 7- and 28-days curing

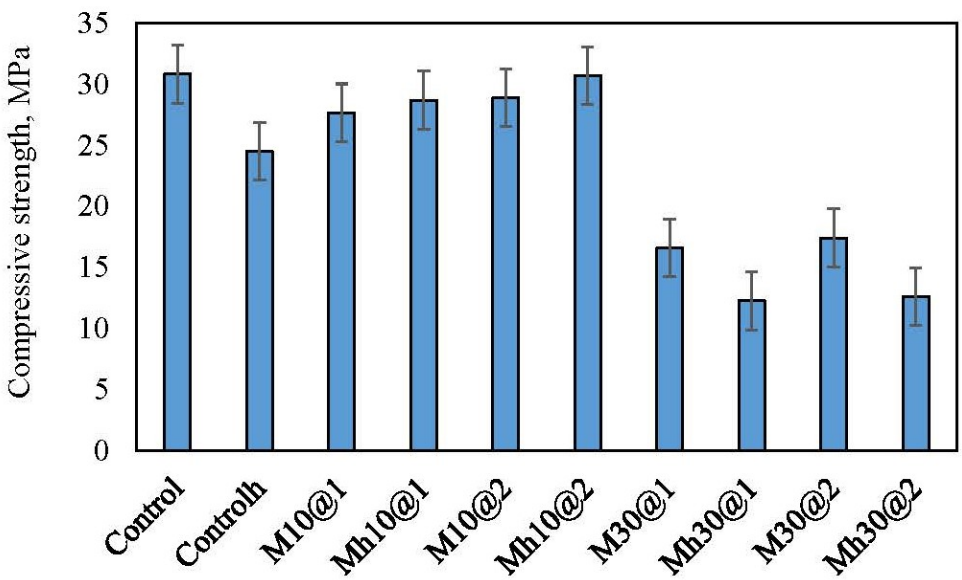
Figures 2 (a and b) show the bar charts together with the error bars for the average of compressive strength results at 7 and 28 days for different mixes. The standard deviations of 3 cube samples for each mix were ranged from 0.44 to 0.96 at 7 days age, while the standard deviations were ranged from 0.40 to 1.95 at 28 days as shown in Figure 2. As presented, the standard deviation ranges were relatively low to the corresponding average values of the samples. The maximum coefficient of variation for all the mixes at 7 and 28 days was below 9% which indicated good quality control.

Effect of crumb rubber and steel fibres percentages

The compressive strength results in Figure 2 show that partial replacement of fine aggregate by crumb rubber reduced compressive strength to different degrees depending on the percentage provided. It can be seen from Figure 2 that the 10% partial replacement of fine aggregate by crumb rubber and adding 1% steel fibers to the mix led to compressive strengths of 26.4 MPa and 27.63 MPa after water curing for 7 days and 28 days, respectively. These values are slightly lower than those of the control mix exposed to the same curing period and conditions by 6% and 10%, respectively. This observation agrees with Zukri et al., (2017) who found in their study that 10% crumb rubber and 1 % steel fibers had the greatest compressive strength with slight reduction of 6.87%. Increasing steel fibers to 2% of the concrete mix volume while keeping the crumb rubber content at 10%, provided compressive strength values of 27.53 MPa and 28.90 MPa after 7 days and 28 days, respectively. These values are slightly higher than those mentioned above, but they were still lower than those of the control mix exposed to the same curing period and conditions by 1% and 6%, respectively.



(a) Testing after curing for 7 Days



(b) Testing after curing for 28 days

Figure 2: Compressive strength results for different specimens of studied mixes

The increase in the percentage of fine aggregate replaced with crumb rubber to 30% with the addition of 1% steel fibres resulted in concrete with compressive strength of 14.13 and 16.0 MPa after 7 and 28 days of water curing, respectively. These results were far lesser than those of the control mix by 49% and 46%, respectively. Increasing steel fibre content to 2% resulted in compressive strength values of 15.23 MPa and 17.40 MPa, which were also far lesser than the control mix by 49% and 43%, respectively, but higher than those of 1% steel fibres subject to the same curing periods and conditions. It can be argued that increasing the crumb rubber to 30% resulted in poor bonding between the cement particles and crumb rubber, and as a result of additional stresses that this caused, weaken the bond between the cement paste and steel fibres. This might lead to the non-uniformity of the applied load and, in turn, reduces the strength dramatically.

The current results were in the line with the results of Liu et al., (2018) who reported a slight reduction in the compressive strength with the replacement of sand with crumb rubber. Záleská et al. (2019) reported a further reduction of compressive strength as a result of increasing the percentage of crumb rubber. Sofi (2018) reported that the reduction in compressive strength of the mix with 20% crumb rubber was more than 50% compared to the control mix. It was found that the increase in the steel fibres resulted in an increase in the compressive concrete strength results. For example, compressive strength average value for Mix M10@2 shown in Figure 2 which contained 10% crumb rubber and 2% steel fibres was almost the same as the compressive strength value of the control mix at 94% after water curing for 7 and 28 days, respectively. This is in the line with the findings of Sreeshma and Varghese, (2016) who reported that the increase in the steel fibres percentage when combining them with crumb rubber resulted in an increase in the compressive strength of the concrete compared with normal concrete or concrete that included crumb rubber only. As these previous studies utilized commercial steel fibres, it is interesting to note the see a similar trend with the fibres extracted from waste tyres.

Effect of heating on compressive strength

The effects of heating the samples were studied in the mixes designated with the subscript "h", as shown in Figure 2 for oven drying curing (preconditioning) at 105°C for 12 hours. It can be seen from Figure 2 that the compressive strength values of the control mix specimens after oven drying were less than the samples which were tested immediately after water curing for 7 and 28 days by 18% and 20%, respectively.

Unlike normal concrete, rubberized concrete with 10% crumb rubber and 1% steel fibres exposed to oven drying for 12 hours resulted in an increase of the compressive strength for 7 and 28 days when water cured. For instance, mix M_h10@1 compressive strength was higher than that of M10@1 by approximately 5% for 7 and 28 days of water curing. This is in agreement with Mousa (2017) who studied rubberized concrete specimens that included silica fume and exposed to heating that ranged from 105°C to 800°C. He reported an increase in the compressive strength when the temperature was below 300°C. This indicates that by adding 1% waste steel fibres in combination with 10 % crumb rubber may have the same effect as adding silica fume to mixes that include crumb rubber. It can be argued that by adding a small percentage of waste steel fibres (1%) as light reinforcement mixed with the waste crumb rubber strengthens the bond with other binding materials. After oven drying, the little expansion of steel fibres and the heated crumb rubber bound with the other concrete particles in the pore structure may led to slight increase in the compressive strength of the cube.

For higher percentages of steel fibers (2%), compressive strength values of the mix M_h10@2 were slightly higher than those of the mix M10@2 by 2% and 6% after water curing for 7 and 28 days, respectively. For mixes with higher percentage of crumb rubber (30% replacement) and 1% and 2% steel fibres added to the mix, oven drying for 12 hours, reduced the compressive strength by a range of 10% to 28% at both curing periods of 7 and 28 days. This is in the line with the results reported by Abdullah et al., (2018) who reported that the compressive strength reduces with higher rubber content and an increased temperature of heating. Záleská et al., (2019) reported that the rubberized concrete was stable up to 300°C while they mentioned that the decomposition of rubber-based aggregate and its combustion deteriorated functional properties of the samples exposed to 400°C.

3.2 Air Permeability Test Results

The repeatability and reliability of the proposed air permeability test method were checked by carrying out the test on fifteen different cubes of the control mix and for the decay from 100 kPa to 10 kPa. Figure 3 shows the air permeability index in seconds against test number. The standard deviation and coefficient of variation were as low as 2.19 and 2.87%, respectively. Figure 4 shows the decay of air pressure over the specified range. It can be seen from Figure 4 that the regression analysis is approximately linear with a high correlation coefficient, r =0.996.

The variations in the permeability time index for the different mixes studied in this investigation and the error bars are shown in Figure 5. The actual measurements for three specimens per each mix studied were recorded and the average values are indicated in Figure 5. It can be seen that the control specimen that was air dried in the laboratory had the maximum time index with an average value of 75.7 seconds, which is an indication of lowest permeability among the studied specimens.

Oven drying control specimens ($Control_h$) revealed a reduction in time index by 39.2% compared to non-heated samples. Recent advances have shown that the drying regime has a significant effect on the values and repeatability of air permeability results (Yang et al., 2015). It has been argued that drying specimens in the laboratory room temperature for two days led to non-repeatable and misleading results (Dhir et al, 1995; Claisse et al, 1999b). They reported that oven-drying specimens to 105°C for two days led to stable and repeatable results but they reported that the overheating for two days could alter the pore structure of the tested concrete to different degrees depending on the concrete grade. Achang et al., (2019) reported also the significance effect of moisture content on permeability results.

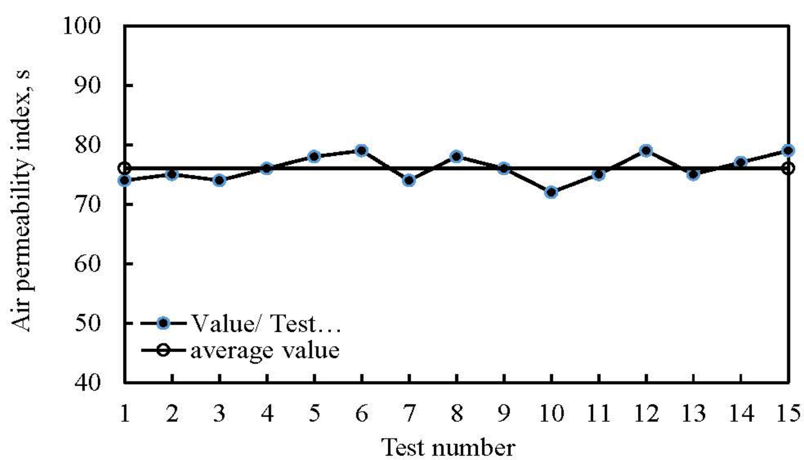


Figure 3: Repeatability of air permeability index for fifteen specimens of the control mix

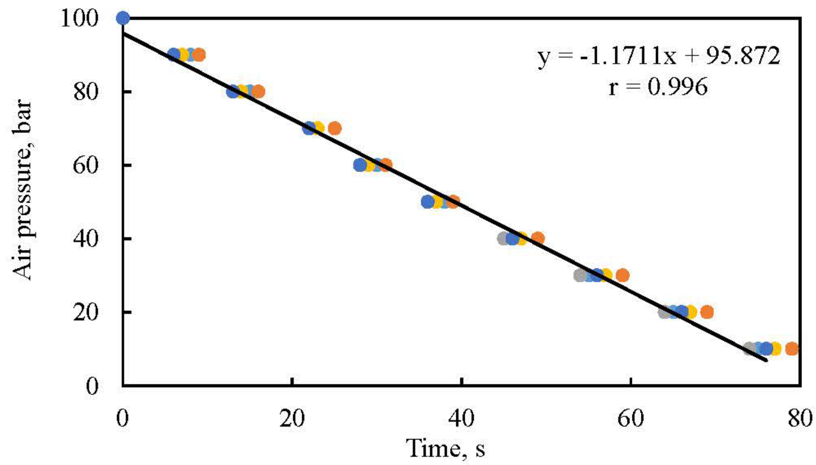


Figure 4: Air pressure decay for many specimens of the control mix

The values of air permeability index for different mixes, shown in Figure 5 revealed that the addition of crumb rubber as a partial replacement of fine aggregate and adding steel fibres to the mix decreases the permeability time index. For example, replacing fine aggregate by 10% crumb rubber and adding 1% steel fibres to the mix, M10@1 resulted in a higher permeability (lower time index) of 23.3% less than that of control specimens. This study shows that oven dried specimens (M_h10@1) had lower permeability before oven drying compared to the normal concrete. This was obtained for the increase in time index to 67 seconds which is the highest time index of those of mixes containing waste tyre extracts. It can be argued that for reasonable partial replacement of fine aggregate with crumb rubber (10%), the rubber expands at high temperatures filling the pores in concrete which expected to reduce the permeability of concrete.

The error bars in Figure 5 show that the standard deviation values of oven-dried specimens were less than those dried at room temperature. Increasing the crumb rubber content to 30% had an adverse effect on concrete permeability and oven-drying specimens having 30% crumb rubber had even lower permeability compared with all other specimens. This may be attributed to the fact that increasing the crumb rubber content more than 10% with steel fibres resulted in higher porosity, which is the most crucial factor for concrete permeability. Liu et al., (2018) reported, an increase in the crumb rubber content resulted in higher water permeability of rubber concrete.

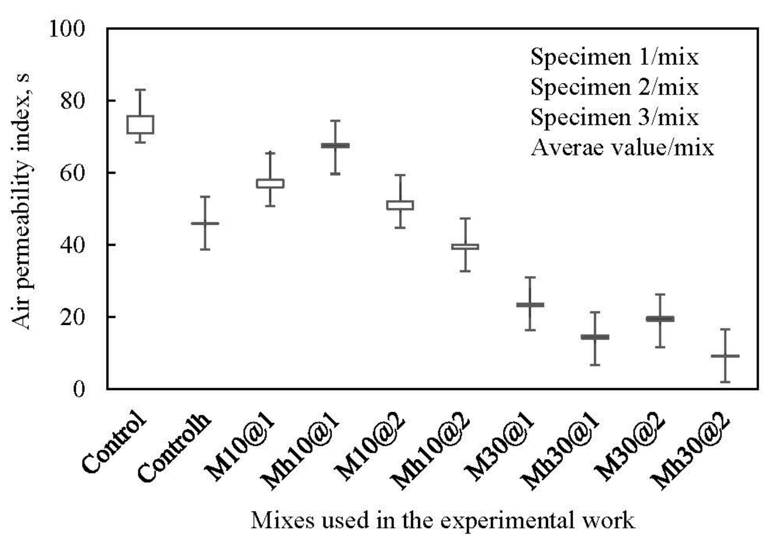


Figure 5: Permeability indices for different specimens of studied mixes

3.3 Air Permeability and Compressive Strength Results Trend

Figure 6 was established based on the results shown in Figures 2 and 5. Figure 6 shows the relationship between the compressive strength and air permeability index after 28 days of concrete curing for different studied specimens under different drying regimes. As shown from Figures 4, 7, and 8, the permeability time index for any mix increase in compressive strength with a linear relationship regardless of the type of mix or the drying regime. The relationship between the air permeability index and the compressive strength showed good correlation with r = 0.91. This agrees with Katapady et al., (2018): they showed that the relationship between the compressive strength and the permeability for a blended concrete containing fly ash and slag cement was linear with a high correlation, regardless of the curing conditions. Furthermore, Cui et al., (2016) also reported a direct relationship between compressive strength and coefficient of permeability. It is worth mentioning that the higher time index indicated lower permeability, and this explains why the relationships between permeability and different mechanical properties in this investigation had the same trend.

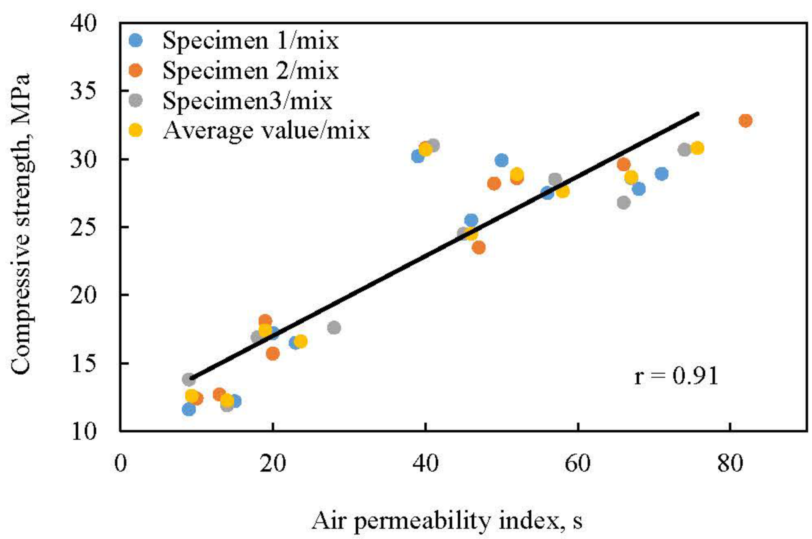


Figure 6: Compressive strength versus air permeability index

4. CONCLUSIONS

The influence of crumb rubber and steel fibres partial replacement of fine aggregate replacement on the compressive strength and air permeability of concrete was considered in this study. A portable easy to use air permeability apparatus was used to test the concrete samples.

The combination of crumb rubber and steel fibres in the concrete mixes led to a reduction of compressive strength and weight of the concrete specimens. An increase in the steel fibres percentage while keeping the rubber content constant resulted in increased compressive strength of concrete. Rubberized concrete of 10% crumb rubber and 1% steel fibres exposed to oven drying at 105°C for 12 hours exhibited an increase in compressive strength.

Replacing fine aggregate with 10% crumb rubber and 1% steel fibres in the mix resulted in a higher permeability (lower time index) by 23.3% less than that of the control specimens. Oven dried control specimens resulted in a higher permeability (reduction of the average time index) by 39.2% compared to that of their air-dried samples.

Oven drying improved the permeability of specimens contain 10% crumb rubber and 1% steel fibres as indicated by a lower permeability (increase in time index) by 15% compared to their air-dried samples. A further increase in the crumb rubber to 30% and oven drying samples had an adverse effect on concrete permeability which was indicated by lower time index (higher permeability).

The relationship between the compressive strength and air permeability index values is linear with a good correlation (r = 0.91), regardless the type of mix or the drying regime.

The experimental results showed a promising application of extracted steel fibres /crumb rubber combination in reinforced concrete. The steel extracted from the waste tyres exhibited a similar performance as commercial steel fibres employed by other investigators.

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