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Mechanical Properties and Air Permeability of Concrete Containing Waste Tyres Extracts

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Abstract

The safe disposal of waste tyres has been seen as having a negative impact on the environment. To mitigate this impact, the components of waste tyres can be used in the production of green concrete. This study explores the effects of the curing and drying regime on the mechanical properties and permeation characteristics of concrete containing both crumbed rubber and steel fibres that are removed from waste tyres. Five concrete mixes were designed and concrete cubes, cylinders, and prisms were cast using waste tyres extracts. 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. Compressive, indirect splitting tensile as well as flexural strengths were conducted after normal curing while observing several drying conditions. Additionally, air permeability was assessed using a portable apparatus which was developed to assess permeability easily. For the concrete test specimens containing 10% partial replacement of fine aggregate by crumb rubber and 1% steel fibres, it was discovered that the splitting tensile strength and flexural strength were higher than that of the control mix by 21% and 22.6%, respectively. For specimens, that included the 10% crumb rubber and 1% steel fibres, when exposed to oven drying at 105°C for 12 hours, the compressive strength results increased by 17% compared to the control specimens exposed to the same conditions. Unlike the compressive strength results, the splitting tensile and flexural strength results decreased after exposing the specimens to elevated temperature. 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. The oven drying curing regime improved the permeability by reducing it in specimens containing the 10% crumb rubber and 1% steel fibres as indicated by increasing their permeability time index by 15% when compared to air-dried specimens. Using waste tyre extracts as a partial replacement of concrete fine aggregate can be recommended for both indoor and outdoor applications. This study showed that this was a viable, economic and environmentally friendly method for reducing carbon footprint.

Keywords: concrete; waste tyres; steel fibres; mechanical properties; air permeability

1. Introduction

In the UK, the waste tyre management industry have been taking great steps in the last ten years to build its proficiency and duty of best practice with safety and environmental legislation (Wrap, 2006). Siddique and Naik (2004) mentioned that over 270 million scrap tyres are deposited in the United States per year. As the potential to reproduce green sustainable concrete, researchers (Ibrahim and Razak, 2016; Tam et al., 2016; Carsana et al., 2013; Aghaee et al., 2015; Rodríguez et al., 2016; Tam et al., 2016; Adeboje et al., 2018-2020) investigated the use of tyre waste in concrete for construction. The advantages gained by using tyre waste 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. Sharobim et al., (2018) reported a higher reduction of tensile strength for specimens overheated in the oven at 300°C. They found a 30% reduction in the splitting tensile strength of overheated rubberized concrete having 10% crumb rubber compared to that of 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). On the other hand, Aiello et al., (2009), Centonze et al., (2012), Sengul (2016) investigated the utilization of steel from waste tyres without adding waste rubber. 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. Crack spacing and crack width were reduced by adding 1% waste steel fibres compared to those of the control specimens.

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 (Segre and Joekes, 2000; Chou et al., 2007; Liu and Zhang, 2015; Guo et al., 2017). Segre et al., (2002) and Mohammadi et al., (2016) suggested that NaOH treatment converts the zinc stearate compound which was used in tyre manufacturing to a soluble form of sodium stearate which can be removed by washing with water. Zukri et al., (2017) studied the effect of treated crumb rubber with the addition of steel fibre on the concrete properties. This resulted in good bonding between cement paste~~s~~ and crumb rubber after treatment with sodium hydroxide (NaOH). The treatment of the crumb rubber was carried out by submerging it in 8 mole of sodium hydroxide for 10 minutes, then dried by a stream of warm air before adding it to the concrete mixes. Roychand et al., (2020) reported similar enhancement in the mechanical properties of the concrete when using treated rubber by sodium hydroxide NaOH.

The quality of concrete can be defined by its durability (Bungey (1989). 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). The water and air permeability of concrete can be used to estimate quality of concrete cover (Yang et al., 2018; Katpady et al., 2018). However, not all permeability tests can be applied on site successfully as they are destructive and sometimes their mobility and setup may be difficult. 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).

Figg (1973) developed tests for determining water and air permeability of concrete in the laboratory and in-situ conditions. The test was based on a hole drilled into the concrete surface. Low pressure was applied to the drilled hole into the surface concrete using a hypodermic needle. The pressure was generated by implementing a vacuum by hand. For the Figg Air test, a hand vacuum pump was used to draw air from a sealed cavity. The Figg air permeability test is measured and evaluated when the pressure recovers from 55 to 50 kPa below the atmospheric pressure in a given time period. However, the apparatus used in this testing method was of considerable expense; further, the hypodermic needle can clog up with debris while applying the pressure. Cather et al.~~,~~ (1984) modified Figg's method by increasing the hole dimensions to 13 mm in diameter and 50 mm in depth. Parrott and Hong, (1991) investigated the air permeability of concrete. They measured the pressure drop from 100 to 95 kPa, for a given period of time, above atmospheric pressure in a sealed cavity; this is known as Permeability Index. However, this test is expensive and difficult to handle on site. 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; Torrent and Gebauer, 1994; Ebensperger and Torrent, 2012). The vacuum technique has been based on vacuum preconditioning and permeability by monitoring pressure decay in concrete cover (concrete near surface). Torrent and Frenzer, (1995); 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 also 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.

2. Research Significance

In this investigation, correlation between the mechanical properties and the non-destructive testing represented in 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 relationship between the mechanical properties and air permeability was evaluated for the studied mixes to explore useful indicators. 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.

3. Experimental Program

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 mechanical properties (compression, splitting tensile, and flexural) of the concrete, a non-destructive air permeability test was used to assess permeation characteristics of studied specimens and to correlate the results with those of the mechanical properties tests. This also provided a simple method for detecting the quality of the rubberized concrete. A detailed discussion now follows.

3.1 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.

3.1.1 Crumb Rubber and Treatment

Crumb rubber was provided in sizes ranging from 2-4 mm by Allcock & Sons Ltd, who specialize in recycling waste tyres and grinding these into crumbs. Figure 1 (a) shows the crumb rubber used in this investigation. Pre- treatment of the rubber crumb was carried out in this research based on the recommendations of Segre and Joekes (2000); Segre et al. (2002); Chou et al. (2007); Liu and Zhang (2015); Mohammadi et al. (2016); Guo et al. (2017; 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.

3.1.2 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). Figure 1 (b) illustrates the steel fibres after extraction and separation.

3.1.3 Cement

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

3.1.4 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.

3.2 Samples Preparation

A total of five mixes were designed: a control mix and four samples 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. Thomaset 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, cylinder specimens of 150 mm diameter and 300 mm height, and prism specimens with cross-section dimension of 100 x 100 mm and length 500 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 105^{o}C 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). For the determination of the tensile and flexural strength, the samples were tested at 28 days (3 samples were tested 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). In total 150 specimens (90 cubes for compressive strength and air permeability testing, 30 cylinders for tensile strength testing and 30 prisms for flexural strength testing) were prepared.

3.3 Test Methods

Concrete cube, cylinder and prism specimens were used to test the compressive, indirect splitting tensile, and flexural strengths as well as air permeability assessment as described in 3.2.

3.3.1 Mechanical Properties Testing

The compressive strength testing of the concrete cubes was as shown in Figure 2 (a). Indirect tensile splitting testing was carried out on the concrete samples according to ASTM C190 (2018) as shown in Figure 2 (b). Flexural strength testing was carried out according to ASTM C348 (2018), as shown in Figure 3.

3.3.2 Development of a Portable Apparatus for Air Permeability Assessment

The air permeability of concrete cover was assessed using a non-destructive portable technique developed especially for this investigation. The effect of drying method, addition of crumb rubber and steel fibres on concrete mixes were assessed using this technique. Air permeability index was assessed based on measuring the pressure decay of compressed air by a portable air compressor to near surface concrete. A hole of 13 mm in diameter and 50 mm in depth was drilled into the specimen surface. The dust was cleared using a small brush. A layer of silicon rubber of approximately 5 mm thickness was applied onto the surface around the hole. On setting, the silicon rubber formed a layer around the hole to eliminate any air leakage at the surface. A new steel probe was developed to obtain repeatable and consistent results. The probe with large washer, as shown in Figure 4 (a), was inserted into the hole and the washer was tightened under a nut to make sure that there was complete air tightness between the washer and the silicon rubber. The probe was connected to the portable air compressor via a reflux non-returnable air valve and a pressure gauge to monitor the air pressure decay. In order to make sure that the decay was only through the concrete hole and there is no leakage from the connections, the apparatus was calibrated by drilling a wooden solid cube, adding the silicon rubber around the hole, inserting the probe, and tighten the nut over the washer. The pressure gauge was monitored for over than one hour and no pressure decay was observed. The latest version of the air permeability portable technique was designed to measure the time index in seconds for the pressure decay from 100 KPa (1 bar) to 10 KPa (0.10 bar). This range of pressure difference was chosen to cover a wide range of studied mixes. The test setup is shown in Figure 4 (b).

4. 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.

4.1 Compressive Strength

This section provides details of the compressive strength results.

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

Figures 5 (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 5. 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.

4.1.2 Effect of crumb rubber and steel fibres percentages

The compressive strength results in Figure 5 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 5 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.

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 5 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.

4.1.3 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 5 for oven drying curing (preconditioning) at 105°C for 12 hours. It can be seen from Figure 5 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.

4.2 Indirect Tensile Strength Results

The following sections provide details of the specimens tested for the indirect tensile strength.

4.2.1 Results of the Indirect Tensile Strength test (28 days water curing)

Figure 6 shows the average values and error bars of the indirect tensile strength results for three cylinder specimens per each mix. The standard deviations were ranged from 0.20 to 0.58. Figure 2 (b) illustrates the crack pattern and failure of cylinder specimens under indirect split tensile testing.

4.2.2 Effect of crumb rubber and steel fibres percentages

It can be seen from Figure 6 that the tensile strength value for mix M10@1, containing 10% crumb rubber as partial replacement of fine aggregate and 1% steel fibres was 2.87 MPa which is higher than that of the control mix by 21%. For the same amount of crumb rubber but increasing the steel fibres to 2%, mix M10@2, the tensile strength value was 3.05 MPa, which is higher than that of the control mix by 29%. The tensile strength value for mix M30@1, having 30% crumb rubber and 1% steel fibres, was 1.65 MPa, which is lower than that of the control mix by 30%. Increasing the steel fibres ratio to 2%, mix M30@2, resulted in a slight increase in tensile strength reaching 1.87 MPa, which is still lower than that of the control mix by 21%. This is in agreement with Sreeshma and Varghese (2016) who reported that concrete containing up to 10% replacement of fine aggregate by crumb rubber and commercial steel fibres revealed a higher tensile strength compared to that of the control mix. Thus, utilizing crumb rubber and waste steel fibres is beneficial in applications requiring increased tensile strengths such as rigid pavements or industrial ground floor slabs.

It was observed that rubberized concrete with small percentage of rubber and steel fibres extracted from tyres behaved in a similar manner to those containing the commercial equivalent. It was also noted that the increase of steel fibres in the mix from 1 to 2% resulted in a slight increase in the tensile strength due to the partial replacement of fine aggregate with 10% crumb rubber and the higher 30% of crumb rubber led to the reduction in the tensile strength.

4.2.3 Effect of heating on Tensile Strength

The effect of heating the specimens in the oven at 105° C for 12 hours can be observed from the bar charts in Figure 6. Unlike the compressive strength values shown in Figure 5, and discussed earlier in Section 4.1.3, all the tensile strength values decreased after exposing the specimens to elevated temperature regardless the percentages of crumb rubber or steel fibres as shown in Figure 6. For instance, rubberized concrete of 10% crumb rubber partial replacement of fine aggregate and 1% steel fibres in the mix, $M_h10@1$, specimens exposed to heating in the oven resulted in a reduction of tensile strength value by 23% compared to that of mix M10@1 (air dried).

For Mix $M_h10@2$, which included 2% steel fibres had a tensile strength value lower than that of mix M10@2, by 25%. This shows that the reduction of tensile strength for overheated specimens in this study were lower than that observed by Sharobim et al., (2018) who studied specimens containing crumb rubber only heated up to 300°C. However, one of the group specimens studied by them and exposed to 70°C showed an almost similar reduction (24.4%). For mixes, which have crumb rubber replacement of fine aggregate by 30%, the reduction of tensile strength as a result of overheating was higher than that for 10% crumb rubber replacement mixes.

Figure 6 shows that tensile strength values for $M_h30@1$ and $M_h30@2$ were lower than those of M30@1 and M30@2 by 35% and 37%, respectively. The results in this study show that concrete mixes with crumb rubber and steel fibres extracted from waste tyres may not be suitable for tension applications under high temperature. Similarly, Li et al., (2019) reported that rubberized concrete could improve the thermal insulation of building enclosures saving energy and reduce CO_2 emissions, but was unsuitable for elevated temperature applications in tension.

It can be argued that oven drying curing (preconditioning) was harsh for the specimens containing the 30% crumb rubber since the crumb rubber is expected to expand and weaken the bond between the aggregate particles and itself with cement paste. This expansion establishes micro cracks which eventually lead to fracture of the specimen.

4.3 Flexural strength results (28 days water curing)

Details of flexural strength test results are considered in the following section.

4.3.1 Results of the Flexural Strength Test (28 days water curing)

Thirty 100 mm square cross-section prism specimens of 500 mm length, as indicated in Figure 3, were prepared and tested for flexural strength after water curing for 28 days. Half of these prisms were tested immediately after curing, while the other half were left in the oven for 12 hours at 105°C. For each mix, 3 prism specimens were tested after the curing period, while, the other three were tested after oven dried and cooling in the room temperature inside the laboratory. The average values of the test results were recorded.

4.3.2 Cracking Behaviour and Failure

Figure 7 shows the flexural failure of a prism specimen. It was observed that cracking~~s~~ occurred prior to failure at the peak load. The recorded peak load was dependent on the crumb rubber and steel fibres percentages. Increasing the crumb rubber resulted in a lower peak load, while, increasing the steel fibres percentage led to increasing the peak load, in the line with Abu Bakar et al., (2017) who studied the effect of the combination of crumb rubber and steel fibres on flexural strength and toughness of concrete. They reported that the post-cracking behaviour of the rubberized concrete slab elements induced more ductility leading to increase in the waste tyre crumb rubber aggregate ratio up to 20%. In addition, Eldin and Senouci (1994) observed that the control specimens were broken into two pieces under loading while the rubberized concrete did not show brittleness under flexural loading. Moreover, Hu et al., (2018) reported that the addition of specific ratios of blended steel fibres in concrete improved the mechanical properties.

4.3.3 Effect of Crumb Rubber and Steel Fibres Percentages

Figure 8 shows the average values of the three specimens per mix and the error bars for the flexural strength results for specimens of different mixes after 28 days water curing. The SD calculated from the test results ranged from 0.15 to 0.67.

Figure 8 shows that the flexural strength value for mix M10@1, containing 10% partial replacement of fine aggregate by crumb rubber and 1% steel fibres was 5.85 MPa. This value is higher than that of the control mix by 22.60%. For the same amount of crumb rubber and 2% steel fibres content, mix M10@2, the flexural strength value was 6.10 MPa, which is higher than that of the control mix by 28%. The flexural strength value for mix M30@1, having more crumb rubber of 30%, and 1% steel fibres, was 2.73 MPa. This value is lower than that of the control mix which was 43%. Záleská et al., (2019) reported that the lowest flexural strength was observed for 30% replacement of fine natural aggregates with fine rubber particles. Increasing the steel fibres ratio to 2% while keeping the crumb rubber percentage at 30% for sample M30@2, resulted in a slight increase in the tensile strength ratio to 2.93 MPa, however, it was still lower than that of the control mix by 39%.

Abu Bakar et al., (2017) reported that an increase in the steel fibres percentage in the combined crumb rubber and steel fiber mix improved the flexural strength. Sreeshma and Varghese (2016) also reported that combining the crumb rubber by 10% fine aggregate replacement and adding steel fibres provide~~s~~ higher splitting tensile and flexural strengths compared to those of normal concrete mix. Sofi (2018) reported that the flexural strength decreased when the amount of rubber was increased from 20 to 30%. Again, the trend shown here suggests that the percentage of rubber should be limited to under 20%. It is worth mentioning that the addition of steel fibres overcomes the reduction in flexural strength as a result of increasing the crumb rubber percentage.

4.3.4 Effect of Heating on Flexural Strength

The effect of oven drying of the prism specimens at 105° C for 12 hours can be seen with error bars in Figure 8. All the flexural strength results decreased after being exposed to elevated temperature in a similar manner to those of the indirect splitting tensile strength, as shown in Figure 6. It was observed that the reduction was very extreme and more than those of the indirect splitting tensile strength values. For example, heated rubberized concrete with 10% crumb rubber replacement of fine aggregate and 1% steel fibres in the mix, $M_h10@1$ had a reduction of flexural strength value by 27% compared to that of the non-heated mix, M10@1. For mix $M_h10@2$, which included 2% steel fibers, the flexural strength value was lower than that of M10@2 by 35%. For mixes having crumb rubber replacement of fine aggregate by 30%, the reduction of flexural strength as a result of heating was higher than that for 10% crumb rubber replacement mixes.

The flexural strength values for mixes $M_h30@1$ and $M_h30@2$ were lower than those of mixes M30@1 and M30@2 by 39% and 46%, respectively. This is in the line with the findings of Sharobim et al. (2018) who reported an almost similar reduction for the group of specimens tested after being exposed to 70°C compared with the other group which was tested at 25°C. The results in Figure 8 show that the reduction of flexural strength values for specimens containing 30% crumb rubber, as a result of heating, is higher than that of compressive strength values for specimens containing the same crumb rubber volume shown in Figure 6.

Zukri et al., (2017) also found that the reduction of flexural strength of heated rubberized concrete containing steel fibres is higher than the reduction of compressive strength for the same concrete mix. The reduction of compressive and flexural strengths may be attributed to the expansion of the crumb rubber at high temperature (105°C). However, the reduction in flexural strength is higher than that of the compressive strength due to the type of applied load and its effect. In compression, the rubber as a compressible material with Poisson's ratio round 0.5 filled the voids and it was prevented by the existence of the coarse aggregate from excessive expansion even with heat curing conditions.

In flexural loading, the tensile forces generated on the rubber increases the possibility of using its inelastic property, that is, (nonlinear elastic stress strain curve of the rubber) reaching fracture of rubber particles. The Poisson effect took place inversely by reducing the size of the particles that were exposed to the tensile forces which, in turn, reduces the strength. In higher temperatures, this inelastic property degraded leading to rapid and more reduction in the flexural strength as observed by Sharobim et al. (2018) for specimens tested after being exposed to 400°C.

4.4 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 9 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 10 shows the decay of air pressure over the specified range. It can be seen from Figure 10 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 11. The actual measurements for three specimens per each mix studied were recorded and the average values are indicated in Figure 11. 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., 2013 and 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.

The values of air permeability index for different mixes, shown in Figure 11 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 (higher time index) 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. Zukri (2017) reported that at high temperature the rubber particles fill the narrow channels in the pore structure and a better pore structured system was observed.

It can be seen from the error bars shown in Figure 11 that the standard deviation values of oven-dried specimens were less than those dried at room temperature in the laboratory. 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, as shown in Figure 11. 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 that an increase in the crumb rubber content resulted in higher water permeability of rubber-modified concrete.

4.5 Air Permeability Index: Correlation with Other Properties

The above section showed that the developed test successfully provided a good measurement for the relative permeability performance of concrete based on mix contents. The following sections demonstrate the influence of air permeability on the mechanical properties of studied concrete.

4.5.1 Air permeability and compressive strength results trend

Figure 12 was established based on the results shown in Figures 5 and 11. Figure 12 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 5, 11, and 12, 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 is in agreement 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.

4.5.2 Air permeability, tensile strength, and flexural strength results trend

The indirect splitting tensile and flexural strengths are distinct measures for strength. As expected, they were significantly different in magnitudes; however, they followed a similar pattern of variation as shown in Figures 6 and 8. Figures 13 and 14 show the indirect splitting tensile strength and air permeability index relationship as well as flexural strength and air permeability index relationship, respectively. The figures show that the relationships in both figures have scattered results with linear relationships of correlation values, r = 0.78, and 0.84, respectively.

These relationships had lower correlation compared to that for compressive strength and air permeability index. This agrees with the findings of Mohamed et al., (2017) where the same pattern and trend of variation between air permeability and both indirect splitting tensile and flexural strengths of concrete having Arabic Gum Biopolymer in its ingredients. Furthermore, Cui et al., (2016) reported also a direct relationship between compressive, flexural strengths 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.

5. Conclusions

The influence of crumb rubber and steel fibres partial replacement of fine aggregate replacement on the mechanical properties and air permeability of concrete was considered in this study. The crumb rubber used was pre-treated with sodium hydroxide prior to adding to the concrete mix.

Five mixes were considered and included 10% and 30% crumb rubber and together with 1% and 2% steel fibres extracted from waste tyres as partial fine aggregate replacement.

A portable easy to use air permeability apparatus was successfully developed and 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.

The splitting tensile strength of the concrete specimens containing 10% crumb rubber and 1% steel fibres was higher than that of the control mix by 21%. An increase in the steel fibres to 2% resulted in slight increase of 9% only. All the splitting tensile strength results decreased after exposing the specimens to an elevated temperature regardless of the percentages of crumb rubber or steel fibres used.

Flexural strength results decreased after being exposed to an elevated temperature in a similar manner to those for the splitting tensile strength results.

Unlike normal concrete, rubberized concrete containing steel fibres provided warning prior to failure in terms of a wide flexural crack which indicated the existence of ductile behaviour in the specimens. Flexural strength of concrete containing 10% crumb rubber and 1% steel fibres was higher than that of the control mix by 22.6%. Increase in the steel fibers content to 2% resulted in a slight increase of flexural strength by 6% only.

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. Other mechanical properties, namely, tensile strength, and flexural strength had lower correlation relationships with air permeability index; however, they had the same trend.

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.

It is recommended that the rubber content is limited to 10% and 1% steel extract for outdoor structural applications. However, higher percentages of these waste tyre extracts can be used for indoor applications. These mixes can be used for pavements and slab on grade applications, where they it would withstand moderate temperatures and provide reasonable flexure performance.

The using of waste tyre materials is considered a sustainable, viable, economic and environmentally friendly method for the production of concrete and would mitigate against the energy used-up in buildings operations as well as reduce carbon footprint.

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

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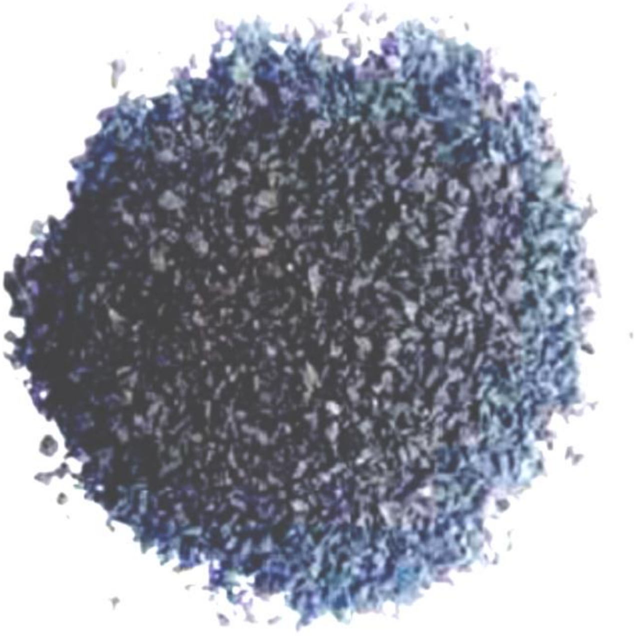


(a) Crumb rubber particles (0.425- 4.75 mm)

(b) Extracted steel fibres

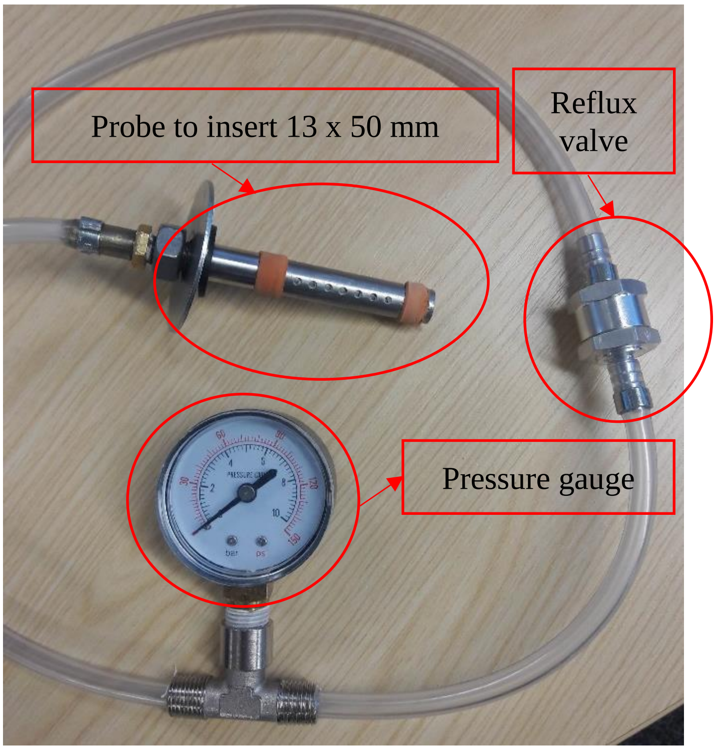
Figure 1: Materials extracted from waste tyres and used in mixes preparation.

(a) Concrete cube sample

(b) Concrete cylinder sample

Figure 2: samples containing 10% crumb rubber and 1% steel fibres; (a) after compressive strength testing, and (b) after splitting tensile strength testing.

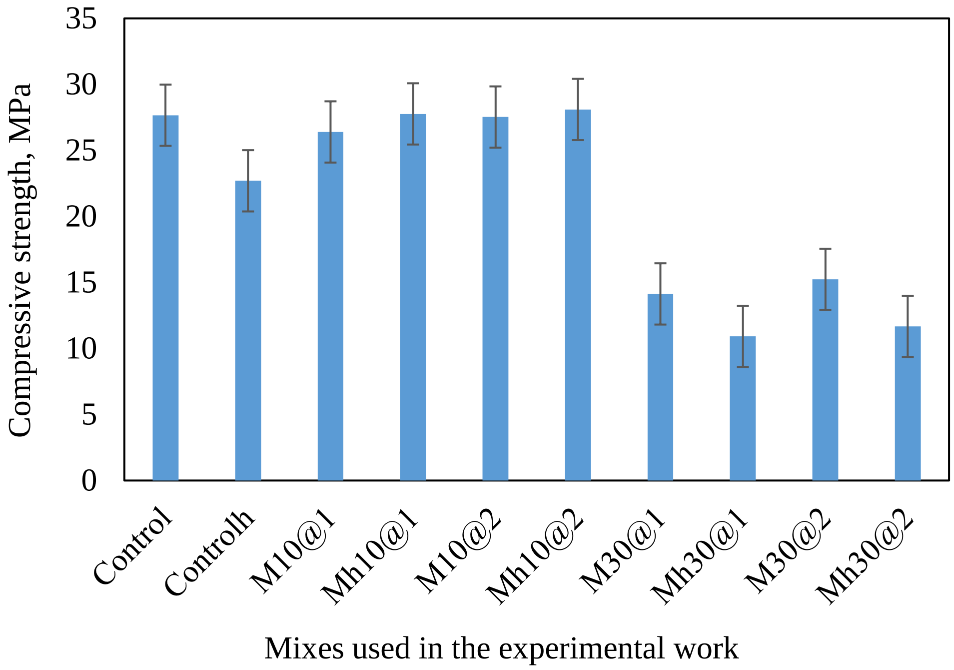
Figure 3: Setup of flexural strength test.



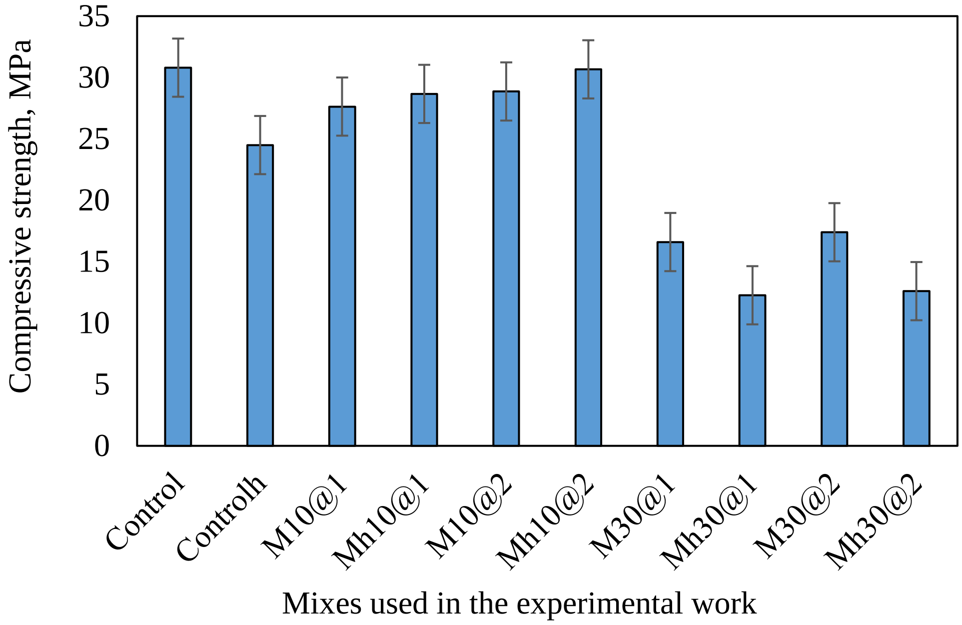
(a) Probe, pressure gauge, and reflux valve.

(b) Test apparatus attached to a portable pump.

Figure 4: Developed portable permeability index test apparatus.



a) Testing after curing for 7 days



b) Testing after curing for 28 days

Figure 5: Compressive strength results for different specimens of studied mixes.

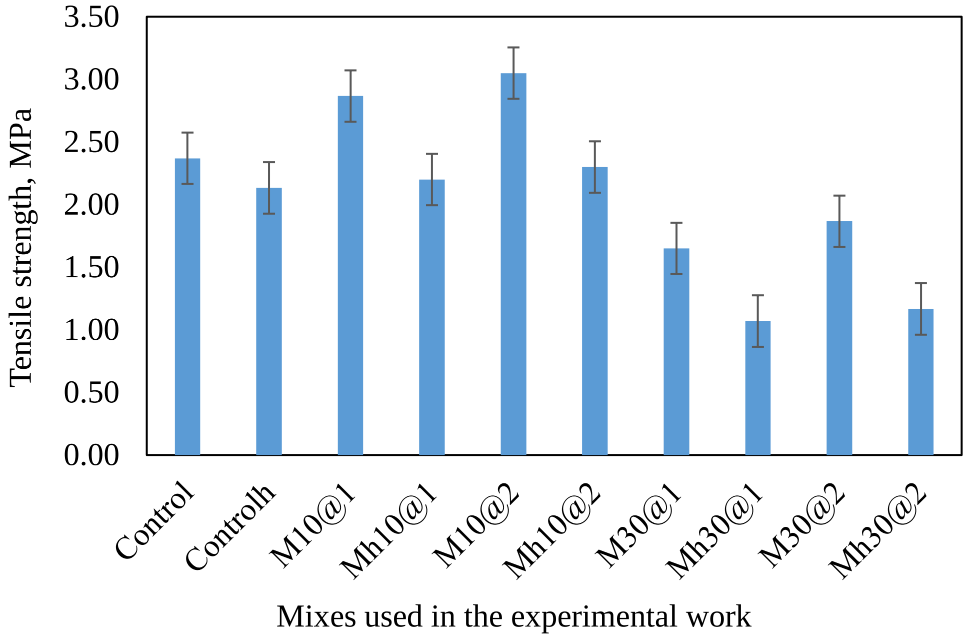


Figure 6: Tensile strength results for different specimens of studied mixes.

Figure 7: Typical failure mode of prism specimen containing crumb rubber and steel fibres

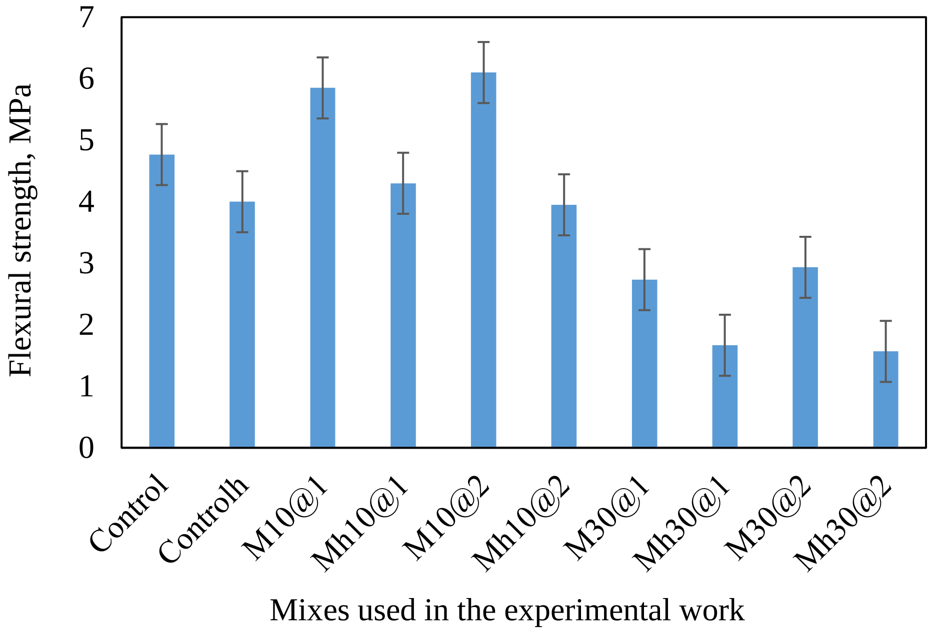


Figure 8: Flexural strength results for different specimens of studied mixes.

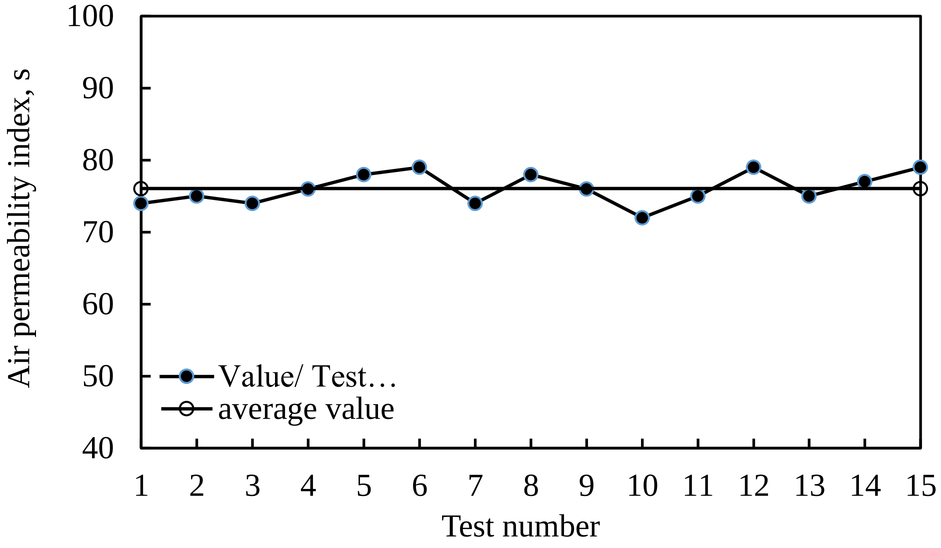


Figure 9: Repeatability of air permeability index for fifteen specimens of the control mix

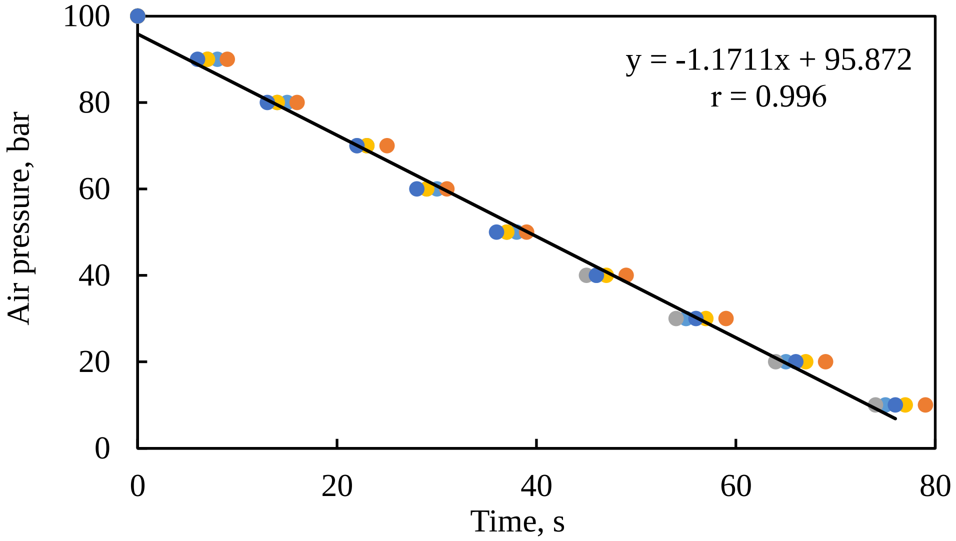


Figure 10: Air pressure decay for many specimens of the control mix

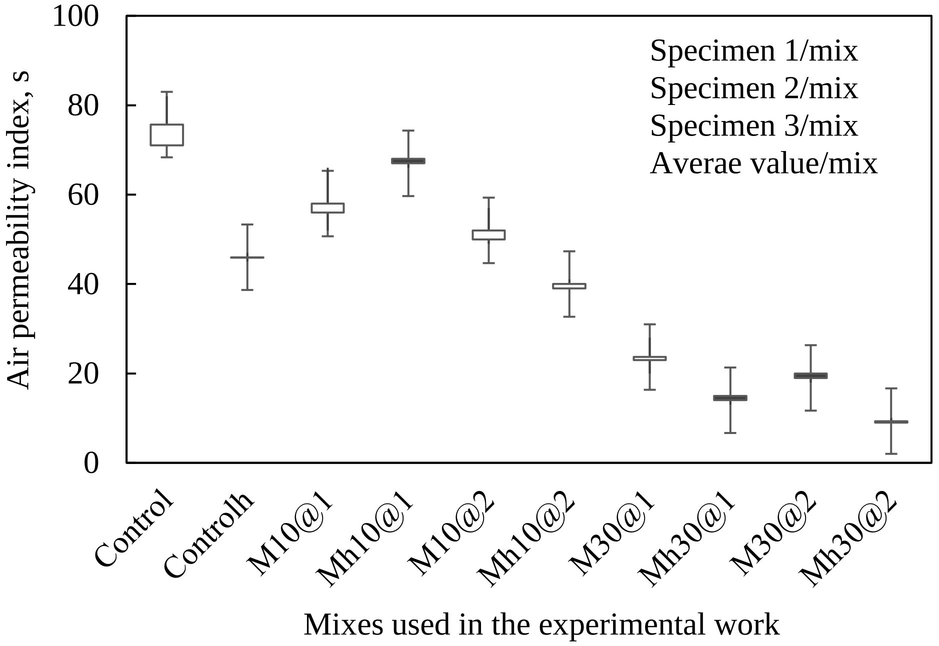


Figure 11: Permeability indices for different specimens of studied mixes.

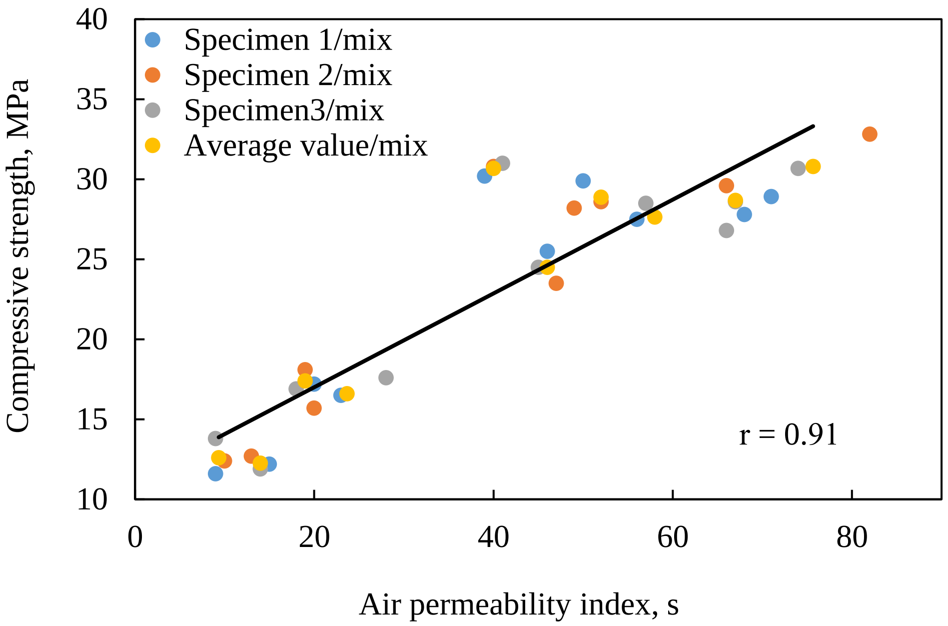


Figure 12: Compressive strength versus air permeability index

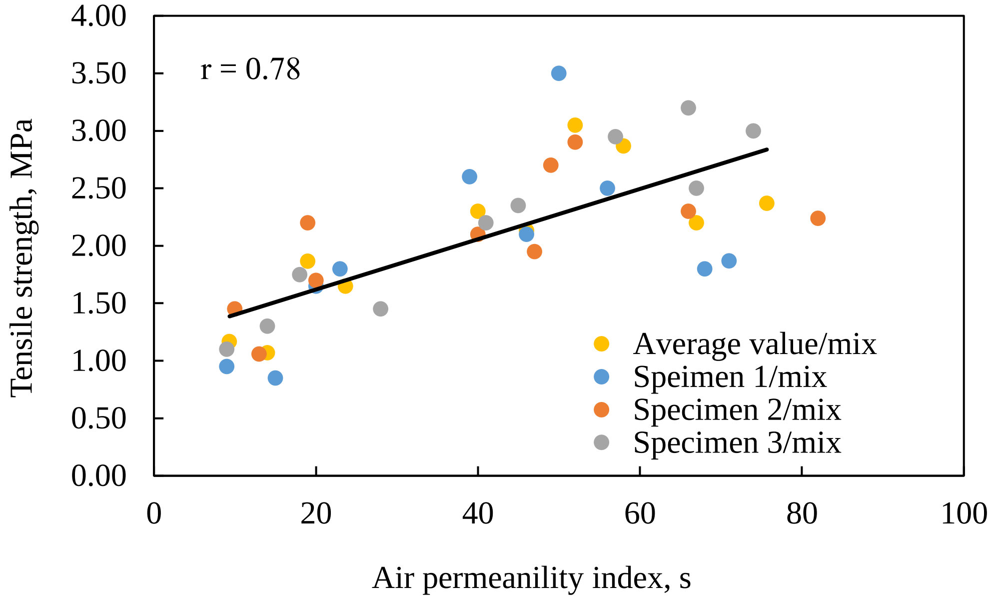


Figure 13: Tensile strength versus air permeability index

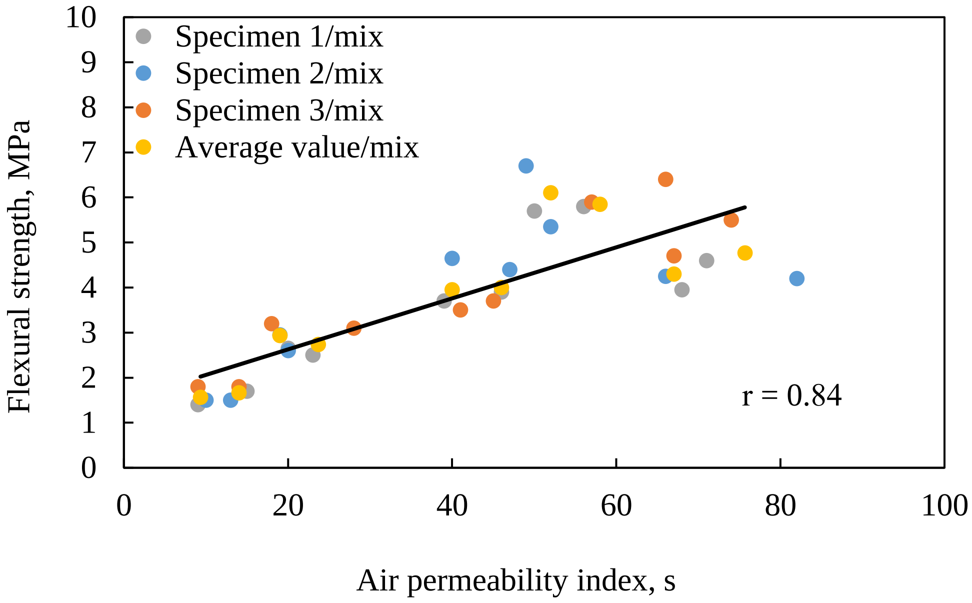


Figure 14: Flexural strength versus air permeability index

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 fibres	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 1 m^3)