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Effect of fine tire rubbers on the compressive strength of concrete with respect to the geometry of the test specimen

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Fine tire rubber
Shape of specimen

Abstract

Worldwide standards give details about the standard size and dimensions of specimen that should be used to determine the compressive strength of concrete. However, these relationships are generally available for plain concrete. Limited information is available regarding the effect of geometry of the test specimen on the compressive strength of concrete incorporating additive materials such as rubberized concrete. In the current work, the effect of incorporation of tire rubber on the compressive strength of concrete has been experimentally investigated. Fine tire rubber particles were added to concrete by 0%, 2%, 4%, and 6% by volume. The results revealed that the compressive strength of concrete decreases linearly as the content of rubber increased. The results also showed that the compressive strength of rubberized concrete depends on the specimen size and slenderness ratio, decreasing as the slenderness ratio increases. Results also revealed that standard cylindrical-to-cubic compressive strength for plain concrete (generally 0.8) may not be applied directly for concrete containing additive materials such as tire rubber. This ratio was found to be equal to approximately 0.72 for C16/20 grade rubberized concrete. Regardless of the test specimen geometry, a strong linear relationship was observed, with each 1% increase in fine rubber content (by volume) reducing the compressive strength of concrete by approximately 6%.

1. Introduction

Production of cement is responsible for 5%-8% of the global human-caused carbon dioxide (CO_2) emissions [1]. This percentage might also increase due to the increasing demand for the production of cement-based materials such as concrete. Some researchers have investigated methods to overcome such a problem and to improve the performance of concrete. Some researchers tried the incorporation of additive materials such as micro- and nano- additive materials into concrete as a partial replacement for cement [1–5] while some others examined the addition of extra materials to concrete such as fibers [6–10]. Tire rubbers are also one of the additive materials that have been reported to improve some of the properties of concrete [11,12]. Tire rubber is commonly utilized into concrete by the partial substitution of aggregates with rubber particles [10,13–16]. This method may not help reduce the amount of cement used in concrete since the quantity of cement is generally held constant. In the current study, fine tire rubbers were added as an extra additive material to the previously prepared concrete obtained from a ready-mixed concrete central. The ready-mixed concrete was transferred to a mixing container. After that, tire rubber particles were gradually added. The obtained mixture was thoroughly mixed until consistent and homogeneous concrete was produced. This approach can help in reducing the quantity of plain concrete than the actual required quantity. Accordingly, the quantity of cement will be reduced.

The use of tire rubber in concrete can also lead to the production of an environmentally friendly and sustainable concrete since tire rubbers incorporated into concrete are generally waste materials. Tires are produced by huge quantities around the world resulting in huge waste tires. The annual quantity of waste tire rubbers is approximately 325 million tires [17]. This quantity is predicted to reach 5 billion tires by the end of 2030 [11,18,19]. Waste tire rubber poses severe environmental hazards such as increasing the contamination of soil, water, and air. They also create a favorable environment for some insects like mosquitoes, by holding water in their cavities and voids for long periods

[11,19–21]. Utilizing of waste tire rubbers into concrete can help reduce these bad effects of waste tire rubber on the environment while improving some important properties of concrete such as energy absorption capacity, impact performance, durability, etc. [11,22,23].

Conversely, use of tire rubbers reduces some other properties of concrete such as compressive strength, tensile strength and flexural strength. This reduction depends on the quantities of the rubber particles used in concrete [12,19,24]. This reduction in strength of rubberized concrete should be taken into account when utilizing this type of concrete. This type of concrete can be used in applications where high strength concrete is not required such as sports area pavements, playground floors, impact barriers, foundation pad in railway station, machinery foundation pads etc. [11,20,25,26]. The incorporation percentage of rubber particles into concrete should also be properly evaluated. Kumar and Dev [27] reported that the use of rubber particles by up to 15% by volume of fine aggregates led to a reduction in the compressive strength that is not very serious. This content reduced the compressive strength by approximately 20%. However, higher contents of rubber particles led to a higher reduction in strength. According to Gravina and Xie [20], the content of tire rubbers in concrete is recommended not to exceed 25% by volume of natural aggregates. This is because of the very low performance of concrete and very high energy consumption related to the recollection and retreading process of tire rubber, which is disadvantageous to the environment.

In general, concrete properties such as compressive strength are size dependent under static and dynamic loads such as impact loads [28–30]. This means that the compressive strength of concrete changes as the size and type of specimen changes. To overcome such a problem, worldwide standards usually give details about the geometry of the test specimens that should be used to evaluate the strength of concrete. In practice, fresh concrete samples are taken in different types (cylinders or cubes) and sizes. While cylindrical specimens are commonly used in some parts of the world, cubic specimens are more common in other parts. In other words, there is no single standard geometry used universally for taking fresh concrete samples for testing. This reflects international differences and local practices. Since cylindrical specimens generally show more suitable results in terms of fracture behavior, cylindrical compressive strength is generally used as the basis in calculations in standards. Conversely, cubic specimens are easier to cast and transport. They can be prepared quickly on-site, removed from mold more easily, and require less material. In addition, cubic specimens have smooth surfaces after being removed from the mold and can be directly tested under compression test. However, cylindrical specimens might need to have their surface leveled after being removed from the molds before they can be tested under compression test, which is an additional work and energy. For these reasons, cubic specimens are frequently preferred. Moreover, the capacity of the test machine might necessitate the use of nonstandard smaller samples instead of the bigger standard ones. This is especially necessary when dealing with high-strength concrete and ultra-high-strength concrete due to their high ultimate load [29]. However, as mentioned before, since cylindrical strength is generally used in the calculation phases in standards, the conversion of test results obtained from specimens of different geometries to their equivalent cylindrical ones must be determined. Numerous studies have been conducted to establish conversion factors between cubic and cylindrical compressive strength test results [29–32]. However, the available relationships are generally provided for plain concrete only.

Conversely, details on the effect of the geometry of the test specimens on the compressive strength of rubberized concrete are scarce. When the literature was explored, it was found that a very limited number of reports have discussed the effect of the geometry of test specimen on the compressive strength of rubberized concrete. Only four reports on this subject could be found in the literature. Valizadeh et al. [33] evaluated the effect of size and type (cubic or cylindrical) of specimen on the compressive strength of self-compacting concrete containing fine rubber particles. Rubber particles were used by 10%, 20% by total volume of aggregates as a replacement of fine aggregates. Their results revealed that the effect of geometry of rubber on the strength of concrete is more pronounced in 20% usage ratio than 10%. Cemalgil and Etli [34] investigated the effect of slenderness ratio (height/width) of prismatic samples on the compressive strength of self-compacting rubberized concrete. Fine rubber particles were used as a partial replacement of sand by 5%, 10%, 15%, and 20% by volume. They found that as the slenderness ratio increases the compressive strength of rubberized concrete decreases. Ferretti [35] studied the effect of type of specimen on the compressive strength of rubberized concrete. Two mixtures were investigated: one plain and one rubberized concrete. The weight of fine rubber particles used in the study accounts for 4.4% of the total weight of the concrete. Two types of specimens were investigated. These are a cube with a width of 150 mm, and a cylinder with a diameter of 150 mm and a height of 300 mm. The test results showed that the ratio between the cylindrical compressive strength to the cubic compressive strength for rubberized concrete is close to that of plain concrete. Zheng et al. [36] investigated the strength, Young's modulus, and brittleness index of rubberized concrete. Cylindrical specimens with dimensions of 150×300 mm and cubic specimens with dimensions of 150×150×150 mm were used in the study. Two types of rubber particles were utilized: fine and coarse rubber particles. The rubber particles were used to replace coarse aggregate by volume at proportions of 15%, 30%, and 45%. The compressive strength test results showed that, for plain concrete, the ratio of cylindrical to cubic strength was 0.72. For rubberized concrete containing small rubber particles, this ratio was 0.68, 0.71, and 0.75 for 15%, 30%, and 45% rubber content, respectively. For concrete with larger rubber particles, the corresponding ratios were 0.64, 0.75, and 0.64. The results revealed that on average rubberized concrete exhibited a slightly lower cylindrical to cubic compressive strength ratio compared to plain concrete.

It can be seen that the available information regarding the size effect of the test specimens on the compressive strength of rubberized concrete is very limited. Since rubberized concrete has poorer workability compared to plain concrete, using cylindrical specimens in practice becomes even more difficult, thereby increasing the need for cubic specimens, which are easier to handle [37,38]. Accordingly, there is a need for size dependence assessment of the performance of rubberized concrete, which has become increasingly used in the construction industry. This shows the need for such a study. The current work provides a detailed experimental investigation on the effect of incorporation of fine tire rubber into concrete on its compressive strength while considering the size effect of the test specimens. Three ratios of fine tire rubbers were investigated (2%, 4%, and 6% by volume of concrete). To contribute to the limited literature regarding this topic, the relationship between the cylindrical and cubic compressive strength of rubberized concrete has been evaluated and a ratio for strength equivalence between them was obtained and compared to that of plain concrete.

2. Experimental study

In the current study, fine rubbers having small particle sizes (less than 4 mm on average) was used (Fig. 1). Sieve analysis and physical properties of the used fine tire rubbers were taken from [11] and are presented in Table 1. The general incorporation procedure of waste rubber particles into concrete found in the literature is as a partial replacement of aggregates. This method requires the addition of tire rubber during the mixing process of concrete. This might be difficult to achieve sometimes considering that concrete used nowadays is mostly obtained from ready-mixed concrete centrals. In this paper, another procedure is tried which depends on the addition of rubber particles to concrete obtained from a ready-mixed concrete central. Rubber particles are added as a ratio of the volume of the prepared concrete mix. This method will allow the addition of rubber particles to the desired quantity of plain concrete while the remaining part of the concrete can still be used as plain concrete. This will also make it easier to produce a functionally graded concrete that contains layers of rubberized concrete and plain concrete. This method is adapted from the method commonly used for fiber reinforced concrete where fibers are added to the concrete at the final stages of mixing [6].

The process involved in the production and preparation of the rubberized concrete consists of the following steps. First, the required quantity of ready-mixed concrete was poured into a bucket of a sufficient size. Then, the previously prepared quantity of the rubber particles (Fig. 1), was added to the mixing container. At this stage, ensuring the homogeneity and consistency of concrete is of great importance. For this reason, rubber particles having an average particle size less than 4 mm were added gradually to the mixing container. At the same time, the mixing process of concrete using a high-speed mixer was continued thoroughly until consistent concrete was obtained. The slow and gradual addition of tire rubbers to the concrete and the thorough mixing of the concrete are very critical in ensuring the consistency of the rubberized concrete. This is because rubber particles have a low specific gravity (1.32) and might tend to float above the concrete mix if added in a large bulk quantity. This will result in a nonuniform dispersion of the rubber particles in the concrete samples, which may affect the results and their reliability. It should be mentioned that since fresh state properties of the concrete were not examined in this study, the consistency of the produced concrete was checked considering the visual consistency. The homogeneity of the concrete was also validated by the standard deviation of the compressive strength test results of tested samples.

After the rubberized concrete was prepared, it was poured into the previously prepared and oiled molds. For each cubic and cylindrical specimen, concrete was added to the mold into three layers and was tamped 25 times using a tamping rod with a diameter of 16 mm and length of 600 mm. Prepared concrete specimens are shown in Fig. 2. After 24 hours, the concrete samples were demolded and put for curing in water curing tanks at a temperature of 20±2 °C. After 28 days, the samples were taken out of the curing tanks and tested under uniaxial compression test. The used compressive strength test device is shown in Fig. 3. It should be noted that the same process was also followed for the preparation of the plain concrete specimens except for the steps involving the addition of rubber particles to concrete.

Table 1. Sieve analysis and physical properties of the used fine tire rubbers [11]

Sieve analysis test results	
Sieve size (mm)	Passing %
16	100
8	100
4	83
2	38
1	2
0.5	0
0.25	0
Fineness modulus	3.77
Physical properties	
Specific gravity	1.32
Compact condition unit weight (g/cm^3)	0.53
Loose condition unit weight (g/cm^3)	0.47

In the current study, three different fine tire rubber contents were evaluated. These are 2%, 4%, and 6% by volume of concrete. These ratios were chosen considering the results reported in the literature. As stated before, the substitute percentage of natural aggregates with tire rubber particles in concrete should be less than 15% - 25% by volume [20,27]. In addition, Döndüren and Al-Hagri [11] reported that the incorporation of fine tire rubber at a content of 10% by volume of fine aggregates reduces the compressive strength of concrete by approximately 32%. Higher content of tire rubber was found to lead to a remarkably higher reduction in the compressive strength. Accordingly, in the current paper, lower usage percentages (lower than 10%) were investigated. Moreover, one plain concrete mix was prepared as a reference concrete. To evaluate the effect of dimensions of the test specimen on the compressive strength of rubberized concrete, specimens of three different geometries were prepared. These include 150×150×150 mm3 cubes, cylinders of 150 mm diameter and 300 mm height, and cylinders of 100 mm diameter and 200 mm height. For each concrete mix, three specimens of each size were examined, and the average value was reported. Samples were tested using compressive strength test that complies with the requirements of the Turkish standard [39]. The loading rate was kept constant as 0.58 MPa/s for all samples, which is within the range given by the standard (0.2-1.0 MPa/s).

Fig. 1. Fine tire rubbers

Fig. 2. Prepared concrete specimens

Fig. 2 Continued

Fig. 3. Compressive strength test device used in this study

3. Results and discussion

Compressive strength tests of all the samples were performed at the age of 28-days. Samples of MR2 concrete after the test are shown in Fig. 4. The average value of three samples for each type of specimens (150×150×150 mm cube, 150×300 mm cylinder, and 100×200 mm cylinder) was calculated. The obtained compressive strength test results are presented in Table 2. The table also presents the standard deviation (σ) for each test set. As can be seen from the table, the used plain concrete is of C16/20 grade concrete, which has a cylindrical compressive strength ranging between 16-20 MPa [40]. It can also be seen that, in general, low values for the standard deviation were obtained for the tested concretes. The average value for the standard deviation for plain concrete is 0.75 MPa and for the rubberized concretes is 1.03 MPa. This is a clear indication that the proposed mixing method of the rubberized concrete can produce concrete of a good consistency. It should be noted that the slightly elevated standard deviation found in some concretes such as MR2 may be related to the localized lower consistency and homogeneity of concrete. Nonuniform dispersion and concentration of rubber particles in different test specimens of the same concrete can lead to a higher variability in the results. This effect can be reduced by increasing the time of mixing and by the slow and gradual addition of rubber particles to concrete during mixing.

To better understand the effect of fine tire rubber on the compressive strength of concrete, the experimental test results are graphically presented in Fig. 5. It can be seen from the figure that addition of fine tire rubber particles reduces the compressive strength of concrete. This reduction was observed to increase as the content of rubber particles increases. Similar tendencies were also reported in the literature [11,41–43]. The reduction values in the compressive strength are presented above the columns in Fig. 5. These values were calculated with respect to the compressive strength of the reference concrete of the same type of specimen (i.e., cube, 150×300 mm cylinder or 100×200 mm cylinder). The maximum reduction percentage was found to be 38.7%, which was recorded from 150×300 mm cylinder of MR6 concrete. The reduction percentage in the compressive strength of MR6 cubic sample, which is 35.7%, is close to that reported in [11] for concrete containing 10% fine tire rubber particles by volume of fine aggregates. They reported the reduction percentage to be approximately 32%. A lower reduction percentage of approximately 17% was reported in [27] for concrete having 10% fine tire rubber particles by volume of fine aggregates. It should be noted that in [27], the surface of the used rubber particles was modified by sulfuric acid. This indicates that the effect of rubber particles on the compressive strength of concrete does not only depend on the usage percentage of rubber particles. It is thought to also depend on other factors such as the compressive strength of the plain concrete, physical properties of rubber particles, etc. More research on this topic can be conducted in the future.

The reduction effect of tire rubbers on the compressive strength of concrete can be attributed to lower load-carrying capacity and strength of tire rubbers. It can be also related to the poor bond between rubber and surrounding concrete and weaker interfacial transition zone (ITZ), which is caused by the hydrophobic nature, shape and texture of rubber particles. Moreover, tire rubber particles have been reported to adversely affect the microstructural properties of concrete by increasing the porosity and cracking of concrete. This has been supported by the scanning electron microscopy (SEM) images reported in the literature. Additionally, rubber particles are softer and deformable compared to cement paste, which results in relative stresses between them. This leads to the initiation and propagation of cracks between the rubber particles and the cement paste. Moreover, due to the high Poisson's ratio and low stiffness of the rubber particles, subsequent tensile stresses are applied to the surrounding cement paste, which reduces its strength. Rubber particles might also tend to move up during the mixing process due to their lower density resulting in a nonuniform concrete [11,21,24,27,43–46].

It's worth mentioning that the reduction effect of tire rubber particles on the strength of concrete can be reduced by the hybrid use of rubber particles with other additive materials such as steel fibers and silica fume [47,48]. The reduction effect can also be reduced by the physical and chemical surface modification of rubber particles with sulfuric acid, NaOH solution, CCl_4 solution, silane coupling agents (such as KH-550, KH-560, and KH-570), NaClO, etc [16,21,27,49].

It can be seen from Table 2 and Fig. 5 that the compressive strength of plain and rubberized concrete is a size dependent property. It is clear that the compressive strengths of the cubic samples are higher than the cylindrical samples for all the tested concretes. However, the compressive strengths of cylindrical samples are close to each other regardless of their sizes. This indicates that the size dependency of the compressive strength of plain and rubberized concrete depends on the height/(width or diameter) ratio, i.e., the slenderness ratio. As the slenderness ratio of the test specimen increases, the compressive strength decreases. This result is in good agreement with the results reported for self-compacting rubberized concrete [34]. Since both tested cylinders have the same slenderness ratio of 2, they have very close compressive strength values. The maximum absolute difference between the compressive strength of 100×200 mm cylinder and 150×300 mm cylinder is approximately 5%. Similar behavior was reported for normal strength and high-strength plain concrete [29,50]. It's important to note that some reports in literature stated that the cubic and cylindrical compressive strength of concrete can vary significantly when the size of specimens varies, even if the slenderness ratio is kept constant. As the size of the test specimen increases, the compressive strength decreases. This change becomes more profound when the size of specimen changes greatly [29,50]. Similar results were also reported for foamed concrete [51] and rock-filled concrete [52].

The ratio of the cylindrical to cubic compressive strength of plain and rubberized concretes are graphically presented in Fig. 6. As can be seen from the figure, the ratio of the 150×300 mm cylindrical compressive strength to the cubic compressive strength of M0, MR2, MR4, and MR6 are 0.77, 0.67, 0.75, and 0.73 respectively. The ratios for the 100×200 mm cylindrical compressive strength are 0.77, 0.70, 0.71, and 0.77 respectively. According to the Turkish standard [40], the ratio of the 150×300 mm cylindrical compressive strength to the 150×150×150 mm cubic compressive strength for plain concrete having a cylindrical compressive strength ranging from 12-20 MPa is 0.8. The corresponding ratio found in this study for plain concrete (i.e., 0.77) is close to this ratio. This ratio was reported to be 0.82 and 0.86 for normal strength and high-strength concrete, respectively [29]. In the case of 100×200 mm cylinder and 100×100×100 mm cube, the ratio was reported to be equal to 0.93 for concrete with a 100×200 mm cylindrical compressive strength of 89.6 MPa [50]. This indicates the conversion ratios of cylindrical to cubic compressive strength of concrete given in the standards should only be used for normal strength plain concrete, not for special concretes.

When the results of plain and rubberized concretes were compared, it was found the ratio of 150×300 mm cylindrical compressive strength to the 150×150×150 mm cubic compressive strength of rubberized concrete is generally lower than the ratio found for plain concrete. For rubberized concrete, this average ratio was found to be approximately 0.72 on average with a standard deviation of 4.35%. This result complies with the findings reported in [36], in which it was reported that rubberized concrete showed lower cylindrical/cubic strength ratio compared to plain concrete. The cylindrical/cubic compressive strength ratio of 0.72 can be used for rubberized concrete having a cylindrical compressive strength ranging from approximately 11-15 MPa and for cylindrical specimens having a slenderness ratio of 2.

This confirms the previous result that the conversion values between the cylindrical and cubic compressive strength of concrete provided in the standards might not be used for additive materials-based concretes such as rubberized concrete. However, more research on this subject is still of a great need.

(a) (b) (c)

Fig. 4. MR2 concrete samples after the test. a) 150×150×150 mm cube, b) 150×300 mm cylinder, c) 100×200 mm cylinder

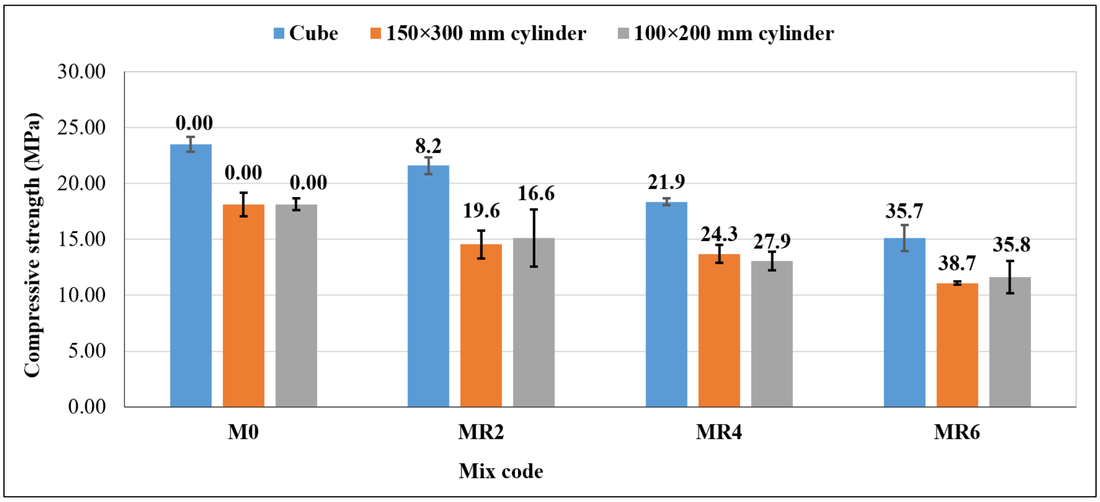

Fig. 5. Compressive strength (MPa) of concrete mixes with different rubber contents (0%, 2%, 4%, 6%)
(Error bars represent the standard deviation values)

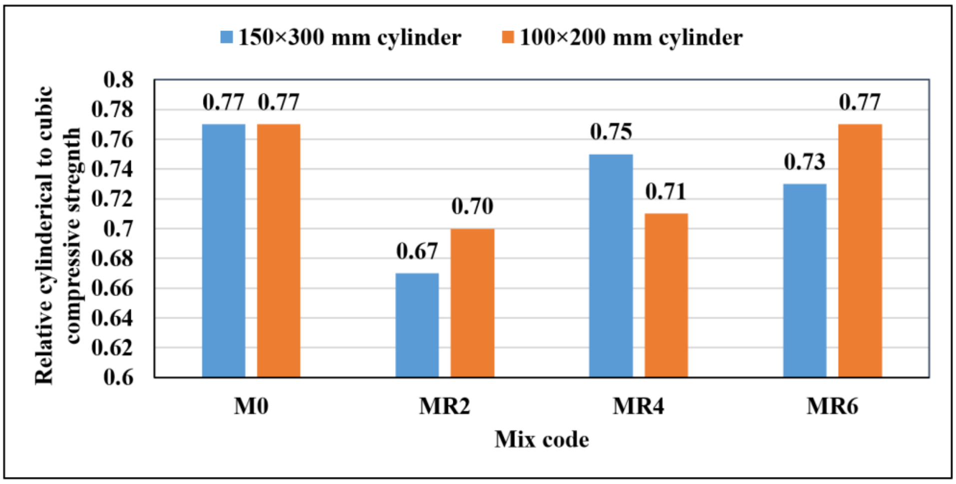

Fig. 6. Ratio of cylindrical to cubic compressive strength values of the examined concretes

Table 2. Compressive strength test results in MPa

Mix code	Content of rubber by volume (%)	Specimen type	Compressive strength (MPa)	σ (MPa)
M0	0	150×150×150 mm cube	23.52	0.67
		150×300 mm cylinder	18.10	1.06
		100×200 mm cylinder	18.13	0.52
MR2	2	150×150×150 mm cube	21.60	0.74
		150×300 mm cylinder	14.55	1.25
		100×200 mm cylinder	15.11	2.55
MR4	4	150×150×150 mm cube	18.36	0.29
		150×300 mm cylinder	13.71	0.80
		100×200 mm cylinder	13.06	0.84
MR6	6	150×150×150 mm cube	15.12	1.16
		150×300 mm cylinder	11.10	0.13
		100×200 mm cylinder	11.64	1.46

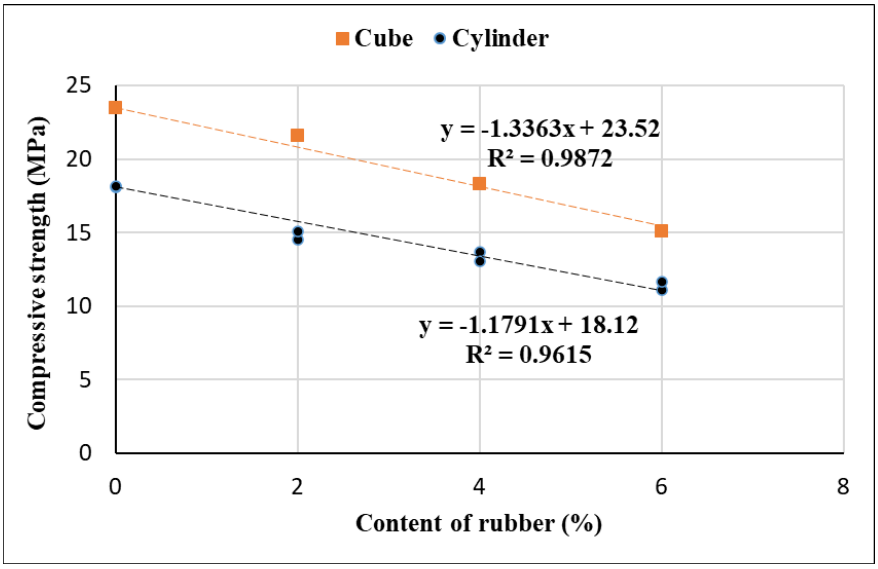

Fig. 7. Relationship between content of rubber (%) and compressive strength of concretes (MPa)

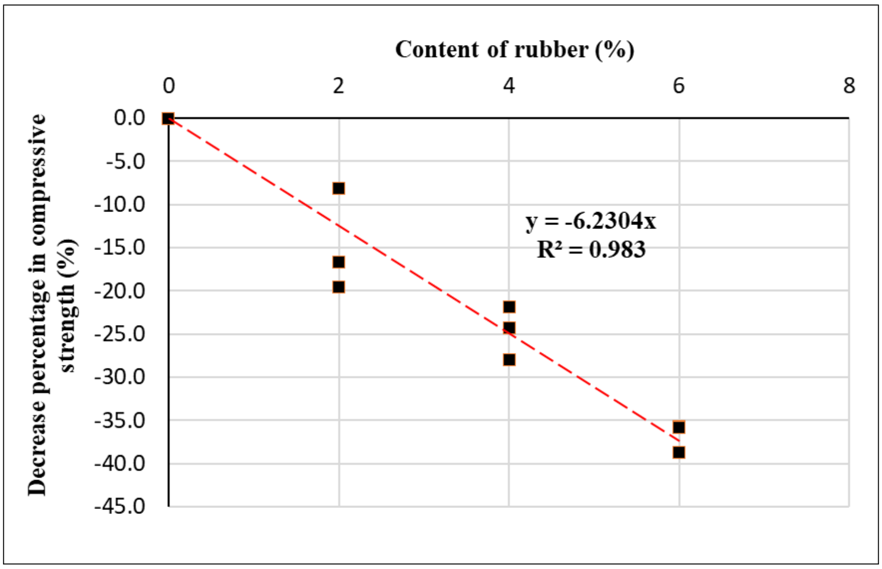

Fig. 8. Reduction in compressive strength (%) of rubberized concrete with respect to content of rubber (%)

It should be noted that different values for the ratio of 150×300 mm cylindrical compressive strength to the 150×150×150 mm cubic compressive strength of rubberized concrete were reported in literature. Valizadeh et al. [33] reported the ratio to be equal to approximately 0.92 for self-compacting plain concrete have a cylindrical compressive strength of approximately 34 MPa. For rubberized concrete, they found that the ratio depends to a great extent on the usage percentage of tire rubber. While the ratio was found to be equal to approximately 0.93 in the case of use of 10% fine tire rubber by total volume of aggregates as a replacement of fine aggregates, it was found to be equal to approximately 0.74 in the case of use of 20% fine tire rubber. Ferretti [35] reported the ratio to be approximately the same for plain concrete and rubberized concrete. The ratio was found to be 0.85 and 0.84 for plain and rubberized concrete respectively. Zheng et al. [36] reported the ratio to be 0.72 for plain concrete having a cylindrical compressive strength of 38.8 MPa. They also reported the ratio to be 0.68 for rubberized concrete with 15% fine rubber particles as a substitution for coarse aggregates and 0.64 for rubberized concrete with 15% coarser rubber particles.

By considering the above-mentioned results and the results reported in some reports in literature, it can be understood that the size dependence of concrete does not only depend on the slenderness ratio of the test samples. It also depends on other parameters such as the compressive strength of concrete, concrete type, aggregate size/gradation, curing conditions, age of specimen etc. [29]. It also depends on the existence and usage percentage of additive materials such as fibers [53]. The size of the used rubber particles can also affect the size dependence of concrete performance [36]. Air void structure and moisture content (dry or wet condition) of the test samples might also affect the size dependence of properties of concrete [35,51]. This reveals the importance of a comprehensive study to expand the available information regarding this topic in literature. The current study tried to supplement the available data by providing a detailed experimental evaluation. However, a more comprehensive study is highly encouraged.

It can be seen from the results that there is a proportional relationship between the content of tire rubber and the reduction percentage of the compressive strength. This relationship is represented graphically in Fig. 7. As can be seen from the figure, there is a linear relationship between the content of rubber and the reduction of the compressive strength for all the tested geometries of specimens. It can also be seen that the reduction percentage that happens in both cylinders is approximately the same regardless of their different sizes. This is because both cylinders have similar compressive strengths. It can also be understood from the high values of the coefficient of determination (R^2) that the relationship between the content of rubber and the reduction of the compressive strength is very strong. High values of R^2 indicate a high-quality relationship and strong correlation between the parameters [6,11,26,54,55].

It is observed from Fig. 7 that the slopes of both fitting equations are close to each other with a difference of approximately 13%. This indicates that there is a relationship between the content of tire rubber and the reduction percentage in the compressive strength of concrete regardless of the geometry of the used specimen. This relationship is graphically presented in Fig. 8. It can be seen from the figure that there is a strong linear relationship with an $R^2 = 0.983$ ($y=-6.2304x$) between the content of fine rubber particles and the reduction percentage of the compressive strength of concrete. This relationship indicates that the reduction in the compressive strength of concrete because of the use of fine tire rubber particles is not related to the geometry of the test specimen. It also indicates that increasing the content of fine rubbers by 1% by volume of concrete will reduce the compressive strength of concrete by approximately 6.2%.

4. Conclusions

In the current study, the effect of rubber particles on the compressive strength of concrete was experimentally evaluated. Fine tire rubber particles were added to concrete as an extra material in three different ratios: 2%, 4%, and 6% by volume of concrete. In addition, the effect of the geometry of the test specimen on the compressive strength of rubberized concrete was evaluated. The relationship between the geometry of the test specimen and the reduction in the compressive strength of rubberized concrete was also discussed. This paper tries to reduce the gap in literature regarding the size effect on the compressive strength of rubberized concrete by providing a detailed evaluation of the relationship between the cubic and cylindrical compressive strength of such concrete. The following results can be drawn from the study:

- Utilization of fine tire rubbers into concrete reduces its compressive strength. This reduction was found to increase as the content of rubber increased. Use of 6% tire rubber reduced the compressive strength by 35.7% - 38.7%.
- The compressive strength of concrete is a size dependent property that depends on the specimen's height to width (or diameter) ratio, i.e., the slenderness ratio. As the slenderness ratio increases the compressive strength decreases. Close values of the compressive strength of cylindrical samples having the same slenderness ratio were found for all the tested samples, with a maximum absolute difference of approximately 5%. On the other hand, the cylindrical compressive strength of concrete was found to be less than the cubic compressive strength. The ratio between these two strengths was found to be 0.77 for the reference concrete that, despite a 3.75% deviation from the standard 0.8 value, falls

well within the expected experimental limits for commercial ready-mixed concrete batches. For the rubberized concrete, this ratio decreased to approximately 0.72 for the tested C16/20 grade. This difference provides further experimental clarity regarding the ratio of cylindrical to cubic compressive strength of rubberized concrete. Within the scope of this study, the ratio of 0.72 shows that the conventional conversion factor of 0.8 may not be directly applicable to rubberized concrete. Therefore, for concrete incorporating additive materials such as rubberized concrete, further research is required to comprehensively determine and systematically standardize these conversion parameters.

- A proportionally reversed linear relationship between the content of tire rubber and the compressive strength of concrete was found for all the examined geometries of the test specimens.
- The geometry of the test sample doesn't affect the reduction that happens in the compressive strength of concrete due to the use of fine tire rubber particles.

In terms of scientific objectivity, it is worth addressing certain limitations of the current study. Although using three replicate specimens per test group (n = 3) meets the minimum requirements specified by TS EN 12390-3 [39] and ASTM C39 [56] standards, a larger sample size would be beneficial to achieve higher statistical power. Furthermore, due to time and laboratory constraints during the fresh-state phase, properties such as slump and air content could not be measured. The authors believe that accounting for these parameters in future investigations on this topic will further enhance the quality and comprehensiveness of the findings. Furthermore, if specimens of a wider variety of dimensions are prepared to expand the scope of investigation, a clearer distinction can be made between the effect of the slenderness ratio and the absolute specimen size effect on compressive strength. Apart from this, the homogeneity of the rubberized concrete specimens was ensured mechanically. Although SEM analysis was considered for verification, budgetary constraints limited its implementation. The authors believe that incorporating this analysis into similar studies would make a positive contribution to the quality of the research.

Symbols and abbreviations

CO_2	Carbon dioxide
ITZ	Interfacial Transition Zone
SEM	Scanning Electron Microscopy
σ	Standard deviation
R^2	Coefficient of determination
M0	Reference concrete mix (0% rubber)
MR2 / MR4 / MR6	Concrete mixes with 2%, 4%, and 6% rubber content respectively by volume

Declarations

Conflict of interests

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Author contributions

All authors contributed equally to this study. All authors have read and approved of the final manuscript and accept equal responsibility for its content.

Data availability statement

The data presented in this study are available on request from the corresponding author.

Use of generative AI and AI-assisted technologies

The author(s) confirm the author(s) did not use any AI tools in the preparation of this work/research/study.

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