Implementation of Regression Analysis and Artificial Neural Network in the Prediction of Rubberized Concrete Mechanical Properties

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ABSTRACT

Recent developments in the field of construction materials established the foundation for the usage of rubberized concrete as a structural material due to its high seismic damping performance. Another objective of the rubberized concrete is to reduce the footprint of wasted rubber by utilizing it as partial aggregate replacement in concrete mixture. Various studies have been conducted to characterize the engineering properties of rubberized concrete. However, none of which presented a generalized model which can be used worldwide to obtain various concrete grades with different rubber replacement percentages. In this study, a comprehensive dataset is collected from over 40 research papers of the published work in the literature. Mathematical predictive models of the engineering properties of rubberized concrete are constructed on the basis of regression analysis and artificial intelligence. Results indicated that regression analysis moderately estimated the engineering properties of rubberized concrete where the coefficient of determination ranged between 0.55 and 0.8. On the other hand, the constructed model through artificial neural network has higher prediction accuracy with a coefficient of determination ranging between 0.82 and 0.96. In addition, this research presented a formula that correlate the compressive strength of rubberized concrete to its static elasticity modulus.

Keywords: artificial neural network, compressive strength, splitting tensile strength, elasticity modulus, flexural strength, regression analysis, rubberized concrete.

ÖZ

İnşaat malzemeleri alanındaki son gelişmeler, yüksek sismik sönümleme performansı nedeniyle kauçuklu betonun yapısal bir malzeme olarak kullanılmasının temelini oluşturmuştur. Kauçuklaştırılmış betonun bir diğer amacı, boşa harcanan kauçuğun beton karışımında kısmi agrega replasmanı olarak kullanılmasıyla kapladığı alanı azaltmaktır. Kauçuklu betonun mühendislik özelliklerini karakterize etmek için çeşitli çalışmalar yapılmıştır. Ancak bunların hiçbiri, farklı kauçuk değiştirme yüzdelerine sahip çeşitli beton kaliteleri elde etmek için dünya çapında kullanılabilen genelleştirilmiş bir model sunmamıştır. Bu çalışmada, literatürde yayınlanan 40'tan fazla araştırma makalesinden kapsamlı bir veri seti toplanmıştır. Kauçuklu betonun mühendislik özelliklerinin matematiksel tahmin modelleri, regresyon analizi ve yapay zeka temelinde inşa edilmiştir. Sonuçlar, regresyon analizinin, tespit katsayısının 0.55 ile 0.8 arasında değiştiği kauçuklu betonun mühendislik özelliklerini orta düzeyde tahmin ettiğini göstermiştir. Öte yandan, yapay sinir ağı üzerinden yapılan model 0.82 ile 0.96 arasında değişen bir belirleme katsayısı ile daha yüksek tahmin doğruluğuna sahiptir. Ek olarak, bu araştırma kauçuklu betonun basınç dayanımını statik elastiklik modülüyle ilişkilendiren bir formül sundu.

Anahtar Kelimeler: yapay sinir ağı, basınç dayanımı, yarılma mukavemeti, esneklik modülü, eğilme dayanımı, regresyon analizi, kauçuklu beton.

DEDICATION

To My Family

ACKNOWLEDGMENT

Wholeheartedly thanks to my dear thesis supervisor Assoc. Prof. Dr Tulin Akçaoğlu for her support, professional guidance and constructive feedbacks along my master's thesis. A special thanks to my parents and my family for their support throughout my program. Lastly, I appreciate all the support and contribution from my colleagues and my friends.

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LIST OF SYMBOLS AND ABBREVIATIONS

ANN	Artificial Neural Network
X_i	Untreated point as collected from the source where $1 \leq i \leq n$
$X_{\eta i}$	Pretreated point through normalization
$\min X_i$	The minimum value in the collected dataset
$\max X_i$	The maximum value in the collected dataset
C	Amount of cement in kg/m^3 in the mixture
W	Amount of water in kg/m^3 in the mixture
ζ	Amount of coarse aggregate in kg/m^3 in the mixture
ϱ	Amount of fine aggregate in kg/m^3 in the mixture
ϖ	The water cement ratio
ς	Admixture content in kg/m^3
ψ	Rubber replacement percentage
ξ	Rubber mass in kg/m^3
Ω	Maximum size of the used rubber
y_i	Targeted engineering property of the rubberized concrete
α_i	Regression fitting coefficient
ϵ	Residual error
$\hat{y}_i$	The predicted output
$\bar{y}$	The average of the measured outputs
H	Hessian matrix
J	Jacobian matrix, which is consisted of the network error derivative with respect neuron weights and bias
∇:	Network error gradient or derivative

e	Error vector
w_k	Neuron weight
I	Identity matrix
μ	Reduction in performance coefficient that varies with every iteration to minimize the error

Chapter 1

INTRODUCTION

1.1 Problem Statement and Objective

Concrete is a composite material which is consisted of aggregates, binder, water and chemical admixture. Day by day, the demand on concrete is spiking due to the high rate of urbanization which resulted in diminishing the natural aggregate resources and threatening their sustainability. For this purpose, alternative sources to replace the aggregate and enhance its engineering properties became a major concerned among researchers. Nowadays, the disposing of old vehicles tires created a tremendous negative impact on the environment including subsoil and freshwater contamination. Not to mention, increasing the risk of wild fires. For this reason, partial replacement of concrete aggregate by shredded rubber tires is investigated by researchers in order to eliminate their negative footprint on the environment. Replacement of aggregate by rubber fragments reduced the compressive strength of concrete. On the contrary, it increases the concrete impact dissipation energy since it increases the general damping behavior. However, current published research in the literature does not generalize the behavior of rubberized concrete. Hence, the aim of this research is to establish a mathematical model which can represent the compressive strength, tensile strength, flexural strength, and elastic modulus of rubberized concrete on the basis of concrete mixture compositions without the need of conducting experimental work.

1.2 Research Strategy

Initially the published worked in the literature is scanned carefully and all presented information regarding the rubberized concrete compositions and the research outputs is collected in tabulated form. The dataset is then randomized and normalized in order to establish a mathematical predictive model through multivariable regression analysis and artificial neural network. The constructed models outputs are compared on the basis of the coefficient of determination and the model with higher coefficient of determination is adopted.

1.3 Thesis Content

This research is composed mainly of five chapters. In this chapter, basic information regarding the rubberized concrete and research methodology is presented.

Chapter 2 presents a wide range background regarding the rubberized concrete and the usage of regression analysis or artificial neural network in predicting the mechanical properties of concrete.

Chapter 3 explains in details the research methodology in collecting the dataset and it also present all the mathematical formulas and computer codes in constructing the mathematical models.

Chapter 4 presents and discusses the effect of individual compositions of rubberized concrete on the compressive strength, splitting tensile strength, flexural strength and elastic modulus. Also it presents and compared among the constructed mathematical models and identified the most significant parameters in predicting the engineering properties of rubberized concrete. Also this chapter illustrates the correlation between compressive strength and modulus of elasticity, as well as compressive strength and splitting tensile strength based on regression analysis. Moreover chapter four shows the effect of different treatment on the compressive strength of rubberized concrete.

Chapter 5 summarized in very compacted manner about the research outcomes and discusses the limitation and recommendations for future studies.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Thu utilization of rubber as a part of concrete has considerable potential to influence the characteristics of concrete in a wide range. Concrete is considered as one of the most widespread building materials. Because of that, the building industry is always working on the increasing its utilizations as well as its applications and aims to enhance its properties. Generally speaking, concrete is weak in the case of tensile strength, concrete has low flexibility as well as low energy absorption. As it's known, during the period of hardening and curing, the concrete tends to shrink and crack. These restrictions are permanently being examined with the aims of improvement by introducing fresh additives and aggregates to be used in the mixture. One of these methods could be the introduction of rubber into the concrete mixture. It is an ideal way to adjust concrete properties and reuse rubber sheets at the same time [1].

With the rapid development of the automotive manufacture in the last years, there is a huge raise in tire waste. Each year, the world has over 1 billion frames. Approximately 21% of these tires are reused in the applications of civil engineering, for utilize as modifiers or additives in asphalt paving as well as cement concrete mixes. Therefore, rubber particles can be utilized as aggregates in cement concrete materials, and they also provide a new method for solving the brittleness of concrete [2].

2.2 Waste Tires

Solid waste treatment is one of the biggest environmental problems around the world due to the increase in the quantities of these materials produced every year. It is evaluated that around 250 million scrap tires are produced each year in Europe. Additionally, for Eastern Europe, North America, Latin America, Japan and the Middle East, the same number is produced every year, while in the US the quantity is approximately 270 million tires. Over the past 30 years, numerous investigations have been carried out in order to estimate the probability of using these materials in different applications in the civil engineering range [3].

2.2.1 Classification of Waste Tires

Many methods have been used to recycle scrap tires, but the preferred one is to grind them before converting them into different applications. After grinding, several sizes of rubber are formed. The different sizes of rubber particles will have different influences on the concrete. (Ganjian et al, 2009) classified scrap tires into two categories: car and truck tires [4]. Car tires differ from truck tires in terms of their ingredient materials, particularly natural and artificial rubber content. Taking into consideration the large production volume of automobile tires compared to truck tires, the former had more concern to investigators. In most of the researches that have been done, three categories of discarded rubber tires are usually considered as shredded, crumb and ground rubbers:

- Shredded or chipped rubber that replace the coarse aggregate. To make this rubber, the tire must be shredded in two stages. At the end of the first stage, the rubber is 300-340 mm long and 100-230 mm wide. In the second stage, its dimensions will change to 100-150 mm by cutting. If the shredding continues further, then particles with a size of 13-76 mm are produced. These are called "shredded particles".

- Crumb rubber that replaces the fine aggregate is made by a special grinder in which large rubber is converted into smaller particles. In this procedure, various sizes of rubber particles can be produced depending on the type of the utilized mill and the temperature produced. With a simple method, the particles are fabricated with a high degree of irregularity in the range of 0.4250-4.75 mm.
- Ground rubber which may substitute cement is relies on the equipment for size lowering. The treated utilized tires are usually undergoing to two stages of magnetic separation and screening. Different sizes of rubber are produced utilizing more complex procedures. In fine grinding process, the particles made are from 0.075 to 0.475mm.

Huang et al. (2004) mentioned in their study that the utilization of smaller size of rubber in concrete is better in order to decrease the possible lowering in the strength of rubberized concrete [5]. Figure 1 shows the different sizes of rubber.

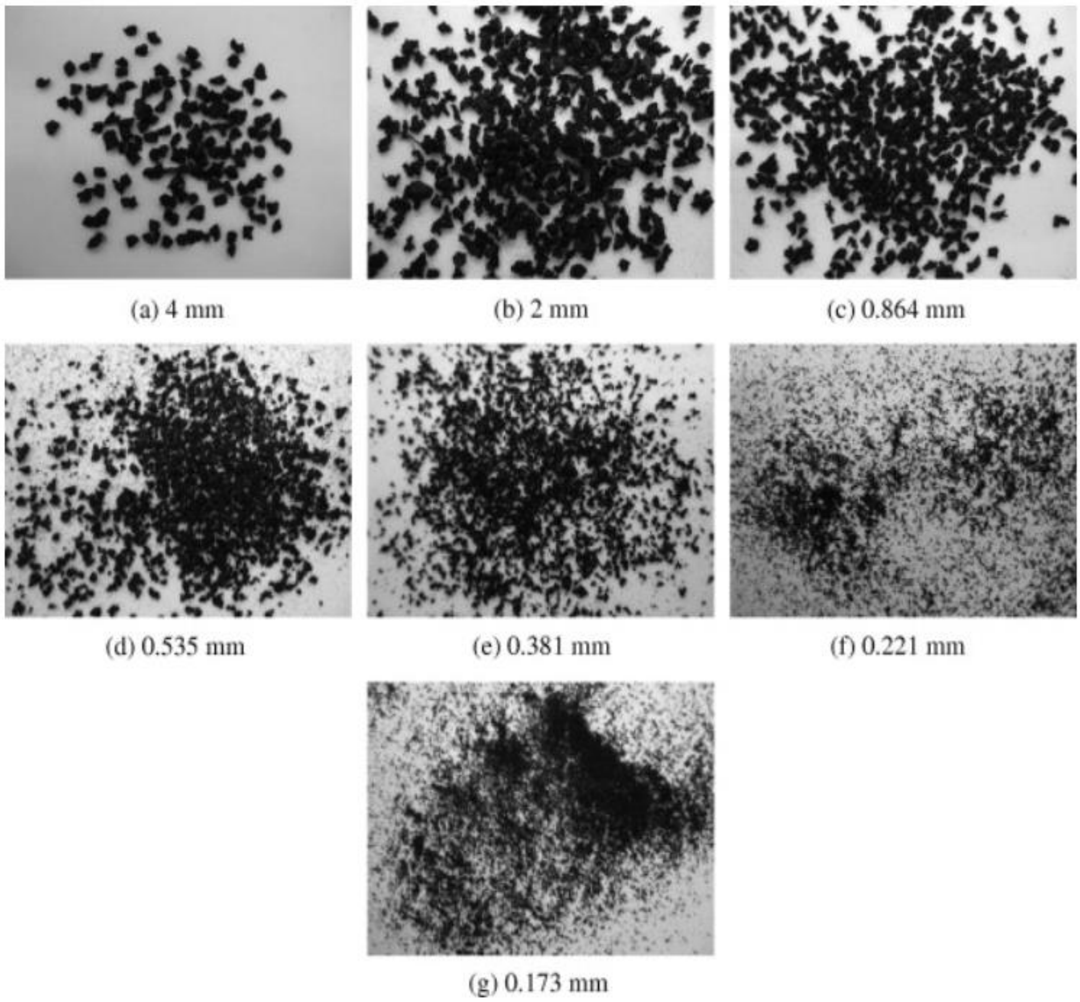

Figure 1: Illustration of Fine Recycled Rubber Particle Sizes [6].

2.3 Components of Concrete

Concrete is a blend of fine and coarse aggregates that are held together by a hardened paste composed of cement and water. The characteristics of concrete differ depending on the utilized components and their proportions in the mixture.

Cement is a hydraulic binder (hardens when mixed with water) that is utilized to produce concrete. Cement paste (composed of cement and water) is held together and hardened by water, in air and under water. The most important things to consider for any cement are: Provides strength with age, and facilitates proper flow properties when fresh.

Aggregates consisting of fine and coarse, represent the granular structure of concrete. As far as possible, all cavities within this skeleton should be filled with binder paste. Total concrete aggregate is about 80% by weight of concrete and 70% by volume of concrete. Optimizing the overall size and quality of the aggregate enhances the concrete quality.

Water is required to chemically react with the cement as well as give workability with the concrete. The quantity of water in the mix compared to the amount of cement is named the w/c ratio. The lower the w/c ratio is, means low permeability and the higher the strength of concrete.

It was found that the utilization of different materials such as industrial wastes in the manufacturing of concrete plays a fundamental role in achieving the required characteristic of concrete.

2.4 Rubberized Concrete

Rubberized concrete refers to concrete with rubber particles as a partial or full substitution of aggregates in it. The application of rubber in concrete production can be dated back to the late 1990s [7]. Rubber concrete has been researched for more than 20 years. Rubber aggregate is mostly obtained from the expired tires that are increasingly discarded, that are known as black pollution because they are not easily degradable, which poses potential fire danger to the environment and provides fertile breeding grounds for mosquitoes. Rubber is commonly utilizing to replace a portion of natural aggregate or as an additive to concrete mixes [8]. There is a general consensus that the plasticity, impact impedance and dynamic energy dissipation capacity increase and compressive strength decrease with the increase in the proportion of the rubber in the concrete because of the elastic and soft nature of the rubber particles. However, conclusions regarding some other characteristics such as workability, bending strength, and freeze-thaw resistance are inconsistent, and even the same property examined by different investigators differs greatly.

The use of rubber tire particles as aggregate in concrete has shown favorable results in the production of a new kind of concrete, which has comparatively enhanced energy absorption, and fracture parameters compared to normal concrete. These properties are very significant for high performance concrete, because due to its high strength, high performance concrete becomes fragile and the rubber filler develops this property, that is, the rubber concrete can absorb more energy or suffer greater deformations before split [9].

2.5 Literature Studies on Rubberized Concrete

In the concrete preparation, coarse and fine aggregate is likely the most rarely used today. Now construction workers need alternatives to replace the natural aggregate. Therefore, finding alternatives to naturally available substances is necessary to the sustainability of the building industry. A review of modern research shows that it is reasonable to utilize industrial products and other materials in preparing concrete as an alternative to cement and aggregates. Crumb rubber tire had utilized as a substitute for sand and its properties were verified. In such cases, waste materials are utilized to adjust the properties of the concrete to make it appropriate for any situation. This would also have more advantages in terms of lowering costs, saving energy, enhancing ecological balance and preserving natural resources.

Güneyisi et al, (2004) presented the mechanical properties of rubber concrete. The test results illustrated that when the amount of rubber increase in the mix from 0 up to 50%, the compressive strength and modulus of elasticity tends to decrease [10]. Ling et al, (2010) study the possibility of utilizing rubber crumb as an alternative to coarse sand in the manufacture of concrete paving blocks. Crumb rubber was treated by using SBR latex. It was concluded that there is a systematic decrease in density and compressive strength with an increase in the rubber amount in the mix [11].

Hamza and Ghedan, (2011) investegated the properties of rubber concrete (compressive strength and thermal conductivity) and compared with the normal concrete. In their study rubber materials were treated by SICAN with 0.1% of water as coupling agent. The test results displayed that adding of rubber materials to the concrete obtains light weight and decreased the compressive strength [12].

Eldin and Senouci, (1993) conducted a study in order to investigate the compressive and tensile strengths of concrete containing rubber. They emphasized that rubberized concrete does not perform as well as ordinary concrete in the case of repeated freeze and thaw cycles. It showed lower compressive and tensile strength than ordinary concrete [13].

Khaloo et al, (2008) stated that replacing the fine aggregates with rubber materials that have small size resulted in the lowest decrease in compressive strength as well as the elastic modulus, but the largest was in case of replacement of coarse aggregates. Ganjian et al, (2009) replaced from 5% to 10% of cement with rubber powder to produce the concrete that caused a decrease in compressive strength and modulus of elasticity of the concrete [14].

Khaloo et al, (2008) carried out a study to examine the effect of substitution at level of 50% of fine aggregates and coarse aggregates with crumb rubber and shredded rubber on the concrete properties. The results showed that, when the amount of rubber increases in the mix, strength and stiffness will decrease [14].

Ganjian et al, (2009) reported that replacing coarse aggregates with shredded rubber at level of 10% in traditional concrete resulted in a raise in water absorption, but in case of replacing cement with ground rubber resulted in a reduction in water absorption [4]. Gupta et al, (2014) noticed how the raise in the water to binder ratio and the size of the rubber materials affects the water absorption. It was concluded that the water absorption increases with increasing both the water to binder ratio as well as the rubber amount, and for the larger rubber particles because of the weak bond between the cement paste and the rubber and thus increased the porosity [15]. Water absorption in self-compacted concrete was examined by Gesoğlu and Güneyisi, (2011) in which FA was substituted with crumb rubber at level of 25% and cement was replaced with fly ash at level of 60%. An advantageous effect in lowering the concrete water absorption when rubber materials were used has been reported [16]. Bisht and Ramana, (2017) substituted the fine rubber with rubber materials at level of 5.5% in the concrete mix and stated that there was a raise in water absorption in concrete when rubber materials were utilized to produce the concrete [17].

The results of the permeability experiment that conducted by Ganjian et al, (2009) showed that the water permeability is higher in the case of replacing of CA with larger rubber materials than in case of replacing of cement with rubber powder [4]. Thomas et al, (2014) utilized different w/b ratios and replaced at level of 20% of FA with CR in traditional concrete. The samples results indicated an increase in the penetration depth for both raised w/b proportion and crumb rubber amount [18]. Su et al, (2015) replaced 20% of fine aggregates with rubber materials that have sizes of 3 mm, 0.5 mm and 0.3 mm separately and finally with constantly grading rubber materials. The results showed that water permeability index was highest for the largest rubber materials [19]. Bisht and Ramana, (2017) replaced at level of 5.5% of fine aggregates with rubber materials in the self-compacted concrete mix and it was noticed that the depth of water penetration tends to go up when the rubber amount increase in the mix [17].

2.6 Compressive Strength of Concrete

Compressive strength of concrete is one of the most substantial properties considered in the construction industry. In some situations, properties, like durability and permeability of concrete are taken in consideration as essential properties, but compressive strength is the main characterization of the concrete quality. Any new concrete mix proposed can only be considered by the construction industry if it satisfies their minimum requirement of the required compressive strength for a structural element [20]. Compressive strength of rubber concrete and mortar differs with the difference in size, ratios, and surface texture of rubber materials.

2.6.1 Effect of Rubber on Compressive Strength of Concrete

The addition of rubber particles as partial substitution of conventional aggregates has a negative influence on the compressive strength of concrete. The strength of the rubber concrete goes down when the rubber content increase in the mix. In addition, the size of the rubber particles also plays a significant role in affecting the strength properties. The compressive strength of the rubber concrete reduces with the raise in particle size. The reduction in strength when the rubber amount increases is due to three major reasons: (i) deformability of the rubber materials relative to the surrounding cement microstructure, resulting in crack initiation in a pattern similar to that of the air voids in traditional concrete, (ii) weak interfacial bond between the tire rubber materials and the cement matrix, and (iii) potential decrease in the concrete matrix density that further depends upon the size, density and the hardness of the aggregates [21].

Khatib and Bayomy, (1999) carried out a study to examine the utilization of recycled tire rubber on concrete properties. During this study, two kinds of rubber were utilized (fine crumb rubber and coarse tire chips). The study was consisting of 3 series of rubberized concrete. In the first one just crumb rubber was utilized and only substituted the fine aggregates. In the second set, tire chips were utilized to substitute the coarse aggregates. In the last group, crumb and chips were utilized. In this group the rubber amount was divided evenly between crumb and chips, once again the crumb substituted the fine aggregates while the chips substituted the coarse aggregates. The rubber amount that utilized in the three series ranged from 5 to 100%. The aggregates were partially substituted by the rubber. The results exhibited a reduction in concrete compressive strength when the amount of rubber increases in the mix, they mentioned that the decrease in strength was considerable, so they recommended to no more than 20% of the aggregate volume be replaced with rubber [22].

Eldin and Senouci, (1993) examined the decrease of compressive strength because of the replacement of coarse and fine aggregates. The study exhibited 85% and 65% decrease in compressive strength when tire chips and crumb rubber were used in concrete production, respectively [13]. In various investigations, it has been stated that replacing of coarse aggregate reduces the compressive strength more than the replacing of fine aggregate [22].

Su et al, (2015) studied rubber concrete mixtures by using 20% of rubber materials with sizes of 3mm, 0.5mm, and 0.3mm separately and finally with constantly grading rubber materials. The results exhibited that σ_c tends to increase when the rubber particles size decrease [19].

2.7 Flexural Strength of Concrete

2.7.1 Effect of Rubber on Flexural Strength of Concrete

Khatib and Bayomy, (1999) carried out a study to examine the utilization of recycled tire rubber on concrete properties. During this study, two kinds of rubber were utilized (fine crumb rubber and coarse tire chips). The study was consisting of 3 series of rubberized concrete. In the first one just crumb rubber was utilized and only substituted the fine aggregates. In the second set, tire chips were utilized to substitute the coarse aggregates. In the last group, crumb and chips were utilized. In this group the rubber amount was divided evenly between crumb and chips, once again the crumb substituted the fine aggregates while the chips substituted the coarse aggregates. The rubber amount that utilized in the three series ranged from 5 to 100%. The aggregates were partially substituted by the rubber. The flexural strength results illustrated a reduction in flexural strength when the rubber amount increase in the mix with a similar manner to that noticed in the compressive strength results. In addition, it was observed that the initial rate of strength lowering was steep compared to that of the compressive strength. This can be attributed to the weak bond between the cement paste and rubber materials [22].

2.8 Splitting Tensile Strength of Concrete

Tensile strength considered as one of the major mechanical properties of concrete. It is the maximum load which it can be applied to concrete before breaking. As its known that concrete is very weak in tension comparing to compression, this is due to its brittle nature. When the concrete is subjected to tensile strength, cracks will progress. Thus, it is necessary to determine the stress that the concrete members might crack.

2.8.1 Effect of Rubber on Splitting Tensile Strength of Concrete

Eldin and Senouci, (1993) studied the effect of size (38, 25, 19, 6.4 and 2 mm) and percentage volume (0, 25, 50, 75 and 100%) of untreated rubber aggregates on the splitting tensile strength of concrete. They observed a 36% loss in strength at 28 days with 25% tire rubber content as coarse aggregate, which increased to 75% loss at 100% replacement level. They found a similar trend in loss of strength with fine rubber aggregates, but the 28-day strengths with fine rubber aggregates were considerably higher than those of coarse rubber aggregates. They noticed a 19% loss in strength at 28 days with 25% tire rubber content as fine aggregate, which increased to 49% loss at 100% replacement level [13].

Topçu, (1995) reported a maximum reduction of 48% and 62% for crumb rubber concrete and coarse tire rubber, respectively, for a replacement level of 45%. Thus, similar to compressive strength reduction, the tensile strength reduction is also higher for coarser rubber particles than crumb rubber in the rubberized concrete mix. The decrease in strength could be because of the increased porosity and corresponding reduction of solid load-carrying material leading to stress concentrations around rubber particles in rubberized concrete [23].

2.9 Modulus of Elasticity of Concrete

Modulus of elasticity is considered as one of the most essential elastic characteristics of concrete as it affects the serviceability and performance of concrete buildings. The modulus of elasticity of concrete is tightly concerning to the features of the cement paste, the hardness of the chosen aggregates, as well as the way of determining the modulus [24].

2.9.1 Effect of Rubber on Modulus of Elasticity of Concrete

Zheng, Huo, and Yuan, (2008) carried out a study to examine the properties of rubberized concrete that produced by substituted the coarse aggregate in traditional concrete with ground and crushed scrap tire rubber in different volume proportions. The modulus of elasticity experiment revealed that modulus elasticity of rubberized concrete reduced with the increasing amount of rubber amount for ground and crushed rubber concrete comparing with traditional concrete. While the percentage of rubber ranged from 15 to 45%, modulus of elasticity for ground rubber concrete decreased from 14.7 to 29.8%, while for crushed rubber concrete the value decreased from 27.5 to 49.5% comparing with the normal concrete [24].

Li and Zeng, (2014) looked at the effect of the particle size and percentage of rubber content on the elastic modulus of rubber concrete. They stated that the elastic modulus increases with the raise in particle size and decreases with the raise in rubber content [6]. Similar observations on the lowering of elastic modulus with the raise in rubber amount were recorded by (Atahan and Yücel, 2012) [25].

Skripkiūnas, Grinys, and Černius, (2007) carried out a study to evaluate the deformation characteristics of concrete that contain rubber waste as an additive. The utilized rubber wastes were crumbed. Rubber was utilized as a substitute for fine aggregate in concrete mixes with a 3.2 % of aggregates mass. From the results, the rubber additives decreased the modulus of elasticity of the concrete. The average modulus of elasticity is 33.3 GPa in traditional concrete and 11 % higher than that in products where rubber was utilized (29.7 GPa). The addition of rubber materials is an effective way to reduce the modulus of elasticity of the concrete and increase the deformability of the concrete [26].

2.10 Prediction and Evaluation of Concrete Properties: Regression Analyses and Artificial Neural Network

2.10.1 Linear Regression

Linear regression is a statistical analysis, which mainly based on modeling a correlation between two types of variable, the dependent variable, response and the independent variable, the predictor. The objective of the regression analysis is to investigate the relationship between the independent variable and the output, in which regression analysis look at if the independent variables are successful predict the output variable, and classify among these independent variable which variable significantly affect the output.

Many researches have focused in using multivariable regression models improves prediction accuracy. Not like the other techniques, statistical models provide more quickly prediction than the other modeling techniques with simple software computing techniques. In recent years, researchers start using the regression analysis to predict mainly the compressive strength, Yeh (1998) [27], used linear regression to predict the compressive strength of high performance concrete, the inputs were cement, fine and coarse aggregates, water, superplasticizer, fly ash, blast furnace slag and curing age, the results shows a coefficient of determination of 0.574. Another studies done by Deepa et al. (2010)[28], and Chou et al. (2011)[29] where also a linear regression analysis were performed for the purpose of predicting the compressive strength of high performance concrete where the same input were used, the results show a weak fit with coefficient of determination that's equal to 0.491 and 0.6112 respectively.

2.10.2 Artificial Neural Network

In the recent years, researchers have used different methods to predict and evaluate different properties of concrete. Instead of waiting 28 days this prediction models offers the rapidity in construction and shows the mechanical properties of concrete. Prediction of concrete mechanical properties based on statistical models has developed keen interest among researchers. Several models have been developed and suggested, such as soft computing technique (artificial neural network) is widely used in statistical modeling. Earliest computing technique developed by McCulloch & Pitts (1943) [30], which is based on well-structured computer network depicting human brain neurons. Rosenblatt [31] introduced Perceptron which is the primal neural network based on learning process called alpha intensification for linear problems. Whereas, to analyze nonlinear systems, Hopfield's model [32] & Bolzman, suggested a crucial neural network model, which is composed on complicated interconnected neurons. To approach a certain model, AI follows a developed neural network in terms of symbolic approach from different paths. Among these approaches multilayered back-propagation learning algorithm developed by Werbos (1988) [33], has several applications and based on these concepts AI can also be utilized to engineering field based on mathematical models [30]. ANN modelling has shown its significance in civil engineering field for examining and establishing relations between complicated variables. One of the drawbacks of ANN modelling is that the model does provide the specific equation for prediction as the model only simulates the outputs for particular inputs given by the researcher unless the network is constructed in similar aspect.

In materials engineering, ANN computing technique is gaining interest among researchers to establish correlations by identifying models and controls. The networks established for different components in previous researches mainly composed of identifying correlations between cement content, amount of fine and coarse aggregate, admixtures and cement or aggregate replacement materials. Topçu et al. [34] conducted a research to predict compressive strength by constructing feed-forward ANN models. In this model, the prediction of compressive strength is conducted for crushed waste materials in autoclaved aerated concrete and researchers concluded that by using ANN model, the properties can be predicted. Several researches based on ANN modelling for rubberized concrete to obtain mechanical properties are available and the model is based on mix design constituents such as cement, fine aggregate, coarse aggregate, pozzolanic material (fly ash), admixture and water-cement ratio. For instance, Topçu et al. [35] conducted another research study to predict waste rubber mortars compressive strength and the experimental outcomes and ANN modelling are in good harmony. Similarly, to predict the long-term effect of adding pozzolanic material in concrete, ANN model showed a significant capability to obtain compressive strength (Saridemir et al. [36]. As mentioned earlier that ANN model can only provide outputs for a particular user based on their data inputs, the networks can be proposed and for such case, an ANN model network is proposed by Gesoglu et al. [34] to predict the rubberized concrete mechanical properties and the influence each parameter is studied. These individual parameters in the mentioned study are cement content, admixture (silica fume), amount of water, aggregates (fines and coarse) and rubber crumbs. The results of ANN model concluded the influence of water content by stating the reduction in strength with increasing water to cement ratio. Similar results are stated in Guneyisi et al. [37] and Uygunoglu et al. [38] research studies. In addition, Uygunoglu et al. [38] states that higher compressive strength is achieved for lower water-cement ratio at particular rubber content. In general, the available research studies on rubberized concrete conclude that reduction of compressive strength is due to increase in porosity due to natural aggregates partial replacement. Therefore, the data selected from literature for this study in prediction of mechanical properties such as compressive strength, splitting tensile strength, flexural strength and static modulus of elasticity is based on developed ANN technique in accordance with nine input parameters.

Chapter 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents in details the procedure behind the selection process of the data points from the published articles in the literature. In addition, it prescribed the followed methods and tools in constructing the mathematical prediction model. Eventually, methods of detecting the most significant parameters influencing these predictive models are also presented.

3.2 Research Strategy

The aim of this study is to predict the engineering properties of rubberized concrete without the need to conduct any experimental effort through the creation of mathematical models based on the existing data presented in the literature. In order to meet this objective, data regarding the mix design of the rubberized concrete and their obtained engineering properties are collected from all current published articles. These collected data are then normalized and randomized for being used in the construction of multivariable regression analysis and artificial neural network. Further analysis is then conducted to evaluate the most accurate method of predictions and the most significant parameters influencing these predictions. Brief summary of the research flow is presented in Figure 2.

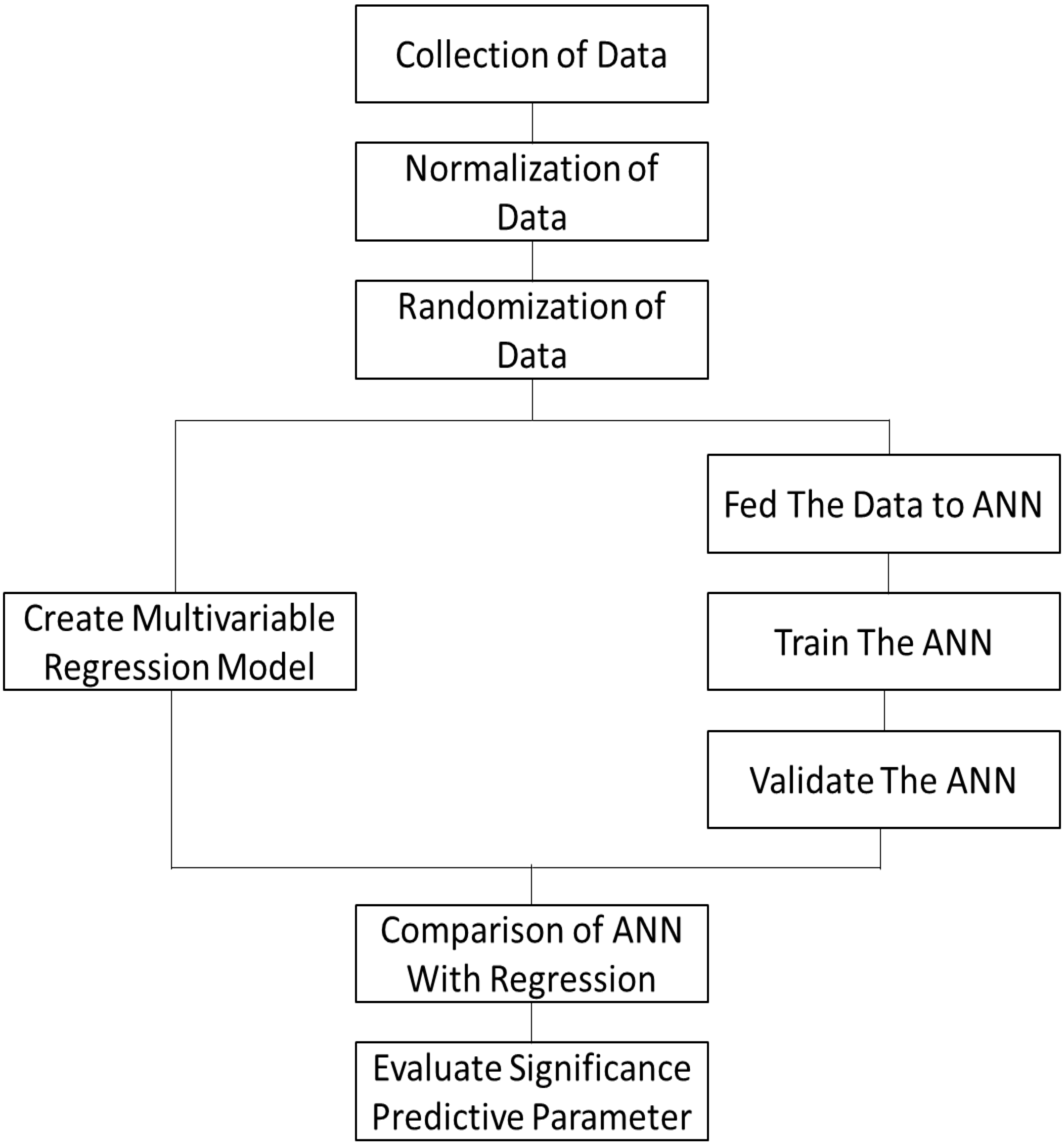

Figure 2: Flow chart of the research strategy.

3.3 Collection of Data

More than 50 articles are used in constructing the database form the published work presented in the current literature. The selection process of these articles is conducted at very sensitive manner. In order to cover wide range of rubber replacements percentages, various physical properties of rubbers regarding their sizes and specific volume, and to cover wide range of structural concrete grades from different sources all around the world. The selected sources are presented in Table 1-4.

Table 1: The collected dataset of the compressive strength of Rubberized Concrete

Rubber Size (mm)	Replacement Level (%)	w/c Ratio	Control Strength (MPa)	Strength Relative to Control (%)	Reference
< 0.3	5, 10, 15, 20	0.35	32.1	92.6, 73.4 73, 68.3	[39]
< 0.6	5, 10, 15, 20	0.35	32.1	86.6, 74.5, 80.5, 68.2	[39]
1	5, 10, 20	0.48	37.2	94.6, 85.5, 79.8	[40]
≤ 1	15, 30, 45	0.62	29.5	66.8, 56.6, 43.4	[41]
1-1.32	15, 30	0.5	39.1	77.2, 54.3	[42]
2	5, 10, 15	0.31	57.8	87.5, 78.4, 65.2	[43]
≤ 2	22.2, 33.3	0.53	33	74.8, 61.2	[44]
< 2	25, 50, 75, 100	0.48	34.1	71.8, 57.8, 44, 37.8	[45]
< 2.5	5, 10, 20, 30, 40, 50	0.48	37.5	80, 65.3, 38.7, 18.1, 10.1, 5.3	[46]
< 4	5, 15, 25	0.35	71.5	81.1,62.9, 37.8	[47]
0.8-4	2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20	0.4	42.5	96.5, 88.2, 87.1, 78.8, 70.6, 58.8, 54.8, 47.1	[48]
< 4	5, 10, 15, 20, 25, 30	0.4	54	92.6, 82.4, 75.6, 64.8, 63.9, 55.6	[49]
0.8-4	2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20	0.45	39	97.4, 84.6, 78.2, 70.5, 64.1, 55.1, 55.1, 51.3	[48]
0.8-4	2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20	0.5	36.5	92.3, 84.1, 80.3, 65.8, 58.4, 50.1, 47.9, 46.6	[48]
< 5	10, 20, 40, 60, 80, 100	0.423	61.7	86.5, 70, 50.6, 33.4, 23.8, 15.6	[50]
< 5	5, 10, 15, 20, 25, 30, 40	0.4	52.95	84.1, 79.5, 70.5, 58, 54.4, 46.7, 33.4	[51]

Table 1 (Continued)

Rubber Size (mm)	Replacement Level (%)	w/c Ratio	Control Strength (MPa)	Strength Relative to Control (%)	Reference
1-5	25, 50, 75, 100	0.57	26.5	84.9, 74.7, 49.8, 32.1	[52]
0-1	5, 10, 20, 30	0.35	64	71.9, 53.1, 21.9, 15.6	[53]
1-2	5, 10, 20, 30	0.35	64	75, 62.5, 34.4, 17.2	[53]
2-3	5, 10, 20	0.35	64	79.7, 73.4, 35.9	[53]
0.178	5, 10, 15, 20	0.35	49.7	92, 82.3, 64.4, 56.5	[54]
1.11	5, 10, 15, 20	0.35	49.7	93.8, 82.9, 74.6, 62.8	[54]
2	5, 10, 15, 20	0.35	49.7	95.6, 86.9, 81.1, 71.6	[54]
0.15-4.75	20, 40, 60, 80, 100	0.56	25.3	74.9, 48.4, 31.9, 17.6, 9.9	[55]
< 4.75	10, 20, 30, 40	0.42	35	128.6, 102.9, 80, 68.6	[56]
0.15 - 0.25	25, 50, 75, 100	0.45	30.8	20.6, 4, 2.6, 1.8	[57]
1-5	15, 30, 50, 75	0.52	27.1	88.4, 75.3, 71.7, 62.9	[58]
0.85	10, 20, 30	0.54	24.3	67.2, 50.6, 21.8	[59]
2.81	10, 20, 30	0.54	24.3	88.6, 53.9, 47.7	[59]
2.6	15, 30, 45	0.44	38.8	86.3, 66.5, 50.5	

Table 1 (Continued)

Rubber Size (mm)	Replacement Level (%)	w/c Ratio	Control Strength (MPa)	Strength Relative to Control (%)	Reference
4-10	10, 15, 20, 25	0.4	43.5	69, 46, 34.5, 26.4	[60]
< 15	25, 50, 75, 100	0.45	30.8	20.6, 4, 2.6, 1.8	[57]
< 12.7	25, 50, 75, 100	0.5	31.9	61.4, 43.3, 31, 23.5	[61]
5-20	10, 20, 40, 60, 80, 100	0.423	61.7	74.4, 53, 41, 25.6, 23.2, 14.1	[50]
5-20	25, 50, 75	0.52	45.8	52.2, 45.6, 38	[58]
5-10	25, 50, 75, 100	0.57	26.5	60.4, 52.1, 25.3, 21.5	[52]
< 38	25, 50, 75, 100	0.48	33.7	55.8, 36.2, 26.4, 19.9	[45]
10-40	5, 10, 15, 20, 25, 30	0.4	54	88, 81.5, 70.4, 62.4, 57, 50.9	[49]
10-50	5, 10, 20, 30, 40, 50	0.48	37.5	73.3, 56, 33.3, 16, 9.9, 6.7	[46]
4.75-25	10, 20, 30, 40, 50	0.49	35	71.4, 51.4, 34.3, 8.6, 14.3	[56]
4	15, 30, 45	0.62	31.7	57.1, 41.9, 28.4	[41]
4-15	15, 30, 45	0.44	38.8	77.6, 54.1, 46.6	[62]

Table 2: The collected dataset of the splitting tensile strength of Rubberized Concrete

Rubber Size (mm)	**Replacement Level (%)**	**w/c Ratio**	**Control Strength (MPa)**	**Strength Relative to Control (%)**	**Reference**
1	5, 10, 20	0.48	3.36	88.9, 86.31, 83.3	[40]
≤ 1	15, 30, 45	0.62	3.21	67.6, 47.6, 35.2	[41]
< 2	25, 50, 75, 100	0.48	3.4	82.3, 70.6, 58.8, 50	[45]
< 4	5, 10, 15, 20, 25, 30	0.4	3.247	79.6, 74.9, 73.9, 70, 67, 65.7	[49]
< 4	20, 30	0.5	3	60, 33.3	[63]
1-4	15, 30, 45	0.62	3.21	46.7, 33, 25.5	[41]
< 5	5, 10, 15, 20, 25, 30, 40	0.4	4.19	99.3, 91.6, 80.2, 69, 62.3, 58.5, 43.4	[51]
10-40	5, 10, 15, 20, 25, 30	0.4	3.247	81.5, 78.5, 75.2, 73.9, 70.8, 69.2	[49]
0-1	5, 10, 20, 30	0.35	3.48	105.7, 88.5, 52.6, 48.9	[53]
1-2	5, 10, 20, 30	0.35	3.48	100.9, 107.5, 88.5, 50.9	[53]
2-3	5, 10, 20	0.35	3.48	105.7, 86.8, 73	[53]
0.15-4.75	20, 40, 60, 80, 100	0.56	2.82	65.2, 52.1, 33.3, 18.9, 7.8	[55]
0.85	10, 20, 30	0.54	2.026	66.6, 59.4, 36.6	[59]
2.8	10, 20, 30	0.54	2.026	93.7, 55.4, 51.1	[59]
2-6	5, 10, 15	0.48	4.382	70.5, 77.99, 57.7	[64]
2-6	5, 10, 15	0.48	4.382	83.9, 71.8, 54.4	[64]

Table 3: The collected dataset of the Flexural strength of Rubberized Concrete

Rubber Size (mm)	Replacement Level (%)	w/c Ratio	Flexural Strength (MPa)	Flexural Strength Relative to Control (%)	Reference
< 2.5	5, 10, 20, 30, 40	0.48	11	37.3, 31.8, 26.4, 15.5, 9.1	[46]
0-1	5, 10, 20, 30	0.35	6.5	63.1, 47.7, 33.8, 27.7	[65]
1-2	5, 10, 20, 30	0.35	6.5	78.5, 72.3, 55.4, 40	[65]
2-3	5, 10, 20	0.35	6.5	81.5, 75.4, 60	[65]
0.4-4	5, 10, 20	0.4	4.129	89.2, 84.5, 80.1	[66]
0.85	10, 20, 30	0.54	7.5	96.7, 93.3, 66.7	[59]
2.8	10, 20, 30	0.54	7.5	98, 88, 83.3	[59]
0.15-4.75	20, 40, 60, 80, 100	0.56	3.68	69.3, 55.4, 37.5, 20.9, 17.4	[55]
1	5, 10, 20	0.48	3.36	89, 86.3, 83.3	[67]
2	5, 10, 15	0.31	5.6	94.6, 91.1, 82.1	[43]
0.8-4	2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20	0.4	5.32	97.7, 94.2, 90.2, 85.2, 78.2, 75.9, 75.2	[48]
0.8-4	2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20	0.45	5.28	100.8, 95.8, 93.6, 88.1, 85.6, 80.3, 76.5, 75.8	[48]
0.8-4	2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20	0.5	5.12	99.2, 96.9, 91.8, 85.2, 82, 81.3, 78.1, 73.4	[48]
1-4	10, 20, 30, 40, 50	0.5	3.1	61.6, 61.6, 46.8, 34.5, 36.1	[68]
< 5	5, 10, 15, 20, 25, 30, 40	0.4	5.78	96.5, 91.3, 86.7, 80.4, 75.6, 68.5, 58	[51]
2-6	5, 10, 15	0.48	8.41	88.6, 84.9, 65.2	[64]
10-15	15, 30, 50	0.52	5.34	95.5, 94.2, 92.7	[58]
5-20	25, 50, 75	0.52	5.34	83.5, 71.8, 71.8	[58]
< 12.7	25, 50, 75, 100	0.5	3.8	92.1, 81.6, 73.7, 63.2	[61]
6	5, 10, 15	0.48	8.41	94.5, 74, 61.3	[64]
4.75-19	10, 15, 20	0.5	5.43	98.5, 69.1, 62.8	[69]
10-50	5, 10, 20, 30, 40	0.48	11	36.4, 26.4, 23.6, 17.3, 10.9	[46]

Table 4: The collected dataset of the elasticity modulus of Rubberized Concrete

Rubber Size (mm)	Replacement Level (%)	w/c Ratio	E (GPa)	E Relative to Control (%)	Reference
0.85	10, 20, 30	0.54	10.7	74.8, 58.9, 47.3	[59]
2.8	10, 20, 30	0.54	10.7	84.1, 74.8, 71.1	[59]
2-3	5, 10, 15	0.4	38.6	85.5, 79.8, 70.7	
1	5, 10, 20	0.48	28.83	91.7, 84.9, 77.8	[67]
< 4	5, 10, 15, 20, 25, 30	0.4	40.97	93.1, 85.7, 79.8, 75.6, 71.1, 65.5	[49]
< 5	5, 10, 15, 20, 25, 30, 40	0.4	33.61	93.8, 91.6, 82, 68.8, 68.5, 59.5, 46.1	[51]
0.15-0.25	25, 50, 75, 100	0.45	7.41	15.5, 4.2, 1.5, 0.5	[57]
0.595-4	10, 20, 30, 40	0.4	42.23	80.8, 37.8, 22.4, 11.4	[70]
0.595-4	10, 20, 30, 40	0.29	56.86	79.8, 57.5, 31.5,19.6	[70]
2.83	15, 30, 45	0.44	32	84.4, 75, 70.3	[71]
0.2-4	10, 20, 40, 60	0.43	34.31	84.2, 63, 44.1, 37.8	[72]
1-2	17.5, 20, 22.5, 25	0.47	33.2	79.3, 76.8, 72.5, 66.9	[73]
4-15	15, 30, 40	0.44	31.8	85, 69.2, 53	[62]
4.75-19	10, 15, 20	0.5	28.84	83.8, 75.9, 69.6	[69]
10-40	5, 10, 15, 20, 25, 30	0.4	40.97	91.7, 84.2, 76.6, 73.8, 69.1, 60.4	[49]
4-10	10, 15, 20, 25	0.4	34.53	65, 52.5, 43.5, 29.9	[60]
< 15	25, 50, 75, 100	0.45	7.41	33.3, 4.2, 1.6, 0.4	[57]

3.4 Normalization of Data

The process of pretreating the database values so its magnitudes range only between zero and one is referred as normalization. Normalization is adopted to reduce the redundancy and iterations in constructing the mathematical predictive models as suggested by Sola, .et al (1997) [74]. The normalization is conducted as presented in Equation 3.1 using the values presented in table 5.

$$X_{\eta i} = \frac{X_i - \min X_i}{\max X_i - \min X_i} \tag{3.1}$$

where;

X_i: Untreated point as collected from the source where $1 \leq i \leq n$.

$X_{\eta i}$: Pretreated point through normalization

$\min X_i$: The minimum value in the collected dataset.

$\max X_i$: The maximum value in the collected dataset.

Table 5: Minimum and maximum magnitudes of the collected mechanical properties

	Minimum	Maximum
Compressive Strength (MPa)	0.5544	71.5
Splitting Tensile Strength (MPa)	0.22	4.382
Flexural Strength (MPa)	0.64	11
Modulus of Elasticity (GPa)	0.03	40.97

3.5 Randomization of Data

The collected dataset is randomized in this research as portion of the selected data is used in constructing the mathematical predictive model and the rest will be used in validating. For this purpose, randomizing the dataset reduce the bias effect and the imbalanced design. This research adopted the simple randomization technique, where computer code assigns every collected cell with a random magnitude that does not match with the other cells. Then the data are sorted from the least magnitude to the highest magnitude. The used computer code in randomizing the data is presented in Figure 3.

```
void main()
{
        int i, j, a, n, c, max, number[50];

        printf("Enter the number of dataset \n");
        scanf("%d", &n);
        printf("Enter the maximum value of random number\n");
        scanf("%d", &max);

        for (i = 0; i < n; ++i)
        randomize();
        {
                number[i] = random(max);

        }
        for (i = 0; i < n; ++i)
        {
                for (j = i + 1; j < n; ++j)
                {
                if (number[i] > number[j])
                                {
                        a =  number[i];
                        number[i] = number[j];
                        number[j] = a;
                        }
                }
        }
}
printf("The randomized values are \n");
for (i = 0; i < n; ++i)
printf("%d\n", number[i]);

}
```

Figure 3: Randomization code for the collected data using C language.

3.6 Predictive Input Variables

Various input parameters are collected to be used in constructing the predictive model through both of regression analysis and artificial neural network. These parameters are selected on the basis of their influence on the engineering properties of concrete as reported by many researchers. These factors are listed in the following bullet points;

- Amount of cement in kg/m^3 in the mixture (C).
- Amount of water in kg/m^3 in the mixture (W).
- Amount of coarse aggregate in kg/m^3 in the mixture (ζ).

- Amount of fine aggregate in kg/m^3 in the mixture (ϱ).
- The water cement ratio (ϖ).
- Admixture content in kg/m^3 (ς).
- Rubber replacement percentage (ψ).
- Rubber mass in kg/m^3(ξ).
- Maximum size of the used rubber (Ω).

3.7 Regression Analysis

Regression analysis on the basis of the mean square error is conducted to estimate the engineering properties of rubberized concrete through multiple variables analysis. The mathematical representation of the multivariable regression analysis is presented in Equation 3.2.

$$y_i = \alpha_1 C_i + \alpha_2 W_i + \alpha_3 \zeta_i + \alpha_4 \varrho_i + \alpha_5 \varpi_i + \alpha_6 \varsigma_i + \alpha_7 \psi_i + \alpha_8 \xi_i + \alpha_9 \Omega_i + \epsilon \quad (3.2)$$

where;

y_i: Targeted engineering property of the rubberized concrete.

α_i: regression fitting coefficient.

ϵ: residual error.

Where the fitting coefficients are obtained through the following mathematical formulations presented in Equation 3.3.

$$\alpha = (X^T X)^{-1} (X^T y) \quad (3.3)$$

where;

X: is the Predictive Input Variables

$$= \begin{bmatrix} C_1 & W_1 & \zeta_1 & \varrho_1 & \varpi_1 & \varsigma_1 & \psi_1 & \xi_1 & \Omega_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ C_n & W_n & \zeta_n & \varrho_n & \varpi_n & \varsigma_n & \psi_n & \xi_n & \Omega_n \end{bmatrix}$$

α: is the fitting coefficients vector = $\begin{bmatrix} \alpha_1 \\ \vdots \\ \alpha_9 \end{bmatrix}$

y: is the Targeted engineering property of the rubberized concrete vector = $\begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix}$

Based on the above equations, Minitab 2019 is used to construct the multivariable regression analysis of the mechanical properties of rubberized concrete.

3.7.1 Coefficient of Determination (R^2)

The accuracy of the fitting is usually calculated through coefficient of determination (R^2) where the fitting is best as R^2 approaches values close to one. The coefficient of determination is calculated in accordance with Equation 3.4

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2} \qquad (3.4)$$

where;

y_i: Is the measured output.

$\hat{y}_i$: Is the predicted output.

$\bar{y}$: Is the average of the measured outputs= $\sum y_i / n$.

- If R^2 is less than 0.3 is considered as there is very weak effective model.
- If R^2 between 0.3 and 0.5 this mostly considered as a weak effective model.
- If R^2 between 0.5 and 0.7 this value is usually considered as Moderate effective model.
- If R^2 is greater than 0.7 this value is in general considered as strong effective model.

3.7.2 P-value

Is the evidence against a null hypothesis, which defined as general statement that there is no relationship between the measured phenomena, p-value represents the probability of an event to take place divided by all possible probabilities. Hence, the smaller the p-value, the stronger the evidence that null hypothesis should be rejected, the smaller p-value means that the input has a significant effect on the output.

3.8 Artificial Neural Network

Another method of constructing mathematical predictive model is artificial neural network which is vastly adopted by many researchers. In this research, neural network consisted of nine inputs and single output is constructed. Both inputs and output layers are connected with two hidden layers. The structure of the network is presented in Figure 3.3. Back propagation method is used which is derived from the basic theory of calculus chain rule. The data are randomized and 70 percent of the data is used in constructing the network. Meanwhile, the remaining part of the dataset is used for testing and validations. The training function of the network is optimized through Levenberg-Marquardt algorithm. Although this method requires more storage, it does converge faster. This algorithm basically depends on solving nonlinear equations by finding the dataset which possess non zero second order derivative. Where the algorithm approaches the solution as the gradient of the network approaches zero or small magnitude ($\nabla = 10E - 8$). This method converge solution in faster manner since it only estimates Hessian matrix without actual computations. The estimation of the Hessian matrix is presented equation 3.5. Then the gradient of the network is calculated as in equation 3.6. Finally, the network weights are updated as in equation 3.7.

$$\mathrm{H} = \mathrm{J}^{\mathrm{t}}\,\mathrm{J} \qquad (3.5)$$

$$\nabla = \mathrm{J}^{\mathrm{t}}\,\mathrm{e} \qquad (3.6)$$

$$w_{k+1} = w_k - [\mathrm{H} + \mu\mathrm{I}]^{-1}\nabla \qquad (3.7)$$

where;

H: is the Hessian matrix.

J: is the Jacobian matrix which is consisted of the network error derivative with respect neuron weights and bias.

∇: network error gradient or derivative.

e: error vector.

w_k: neuron weight.

I: Identity matrix.

μ: is a reduction in performance coefficient that varies with every iteration to minimize the error.

Based on the mention information above nntool in MATLAB2019a is used to construct the neural network the assumption is presented in Table 6.

Table 6: Used setups in creating ANN model in MATLAB2019a

Parameters	**Magnitude**
Number of hidden layers	2
Number of Neurons	9
Iteration	5000
Validation epochs	1000
Admissible error	10E-8

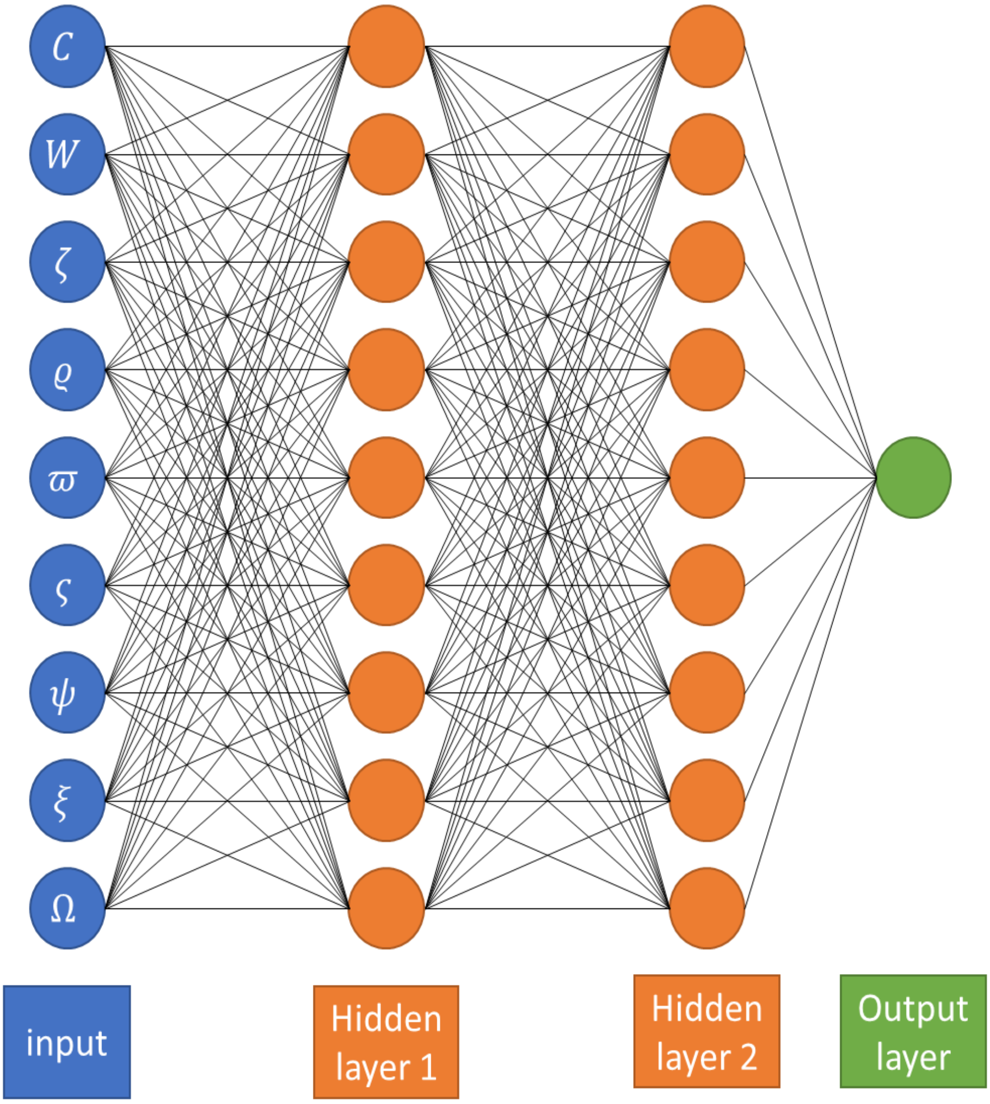

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Figure 4: The structure of the constructed neural network.

Chapter 4

RESULTS AND DISCUSSION OF RESULTS

4.1 Introduction

This part of the thesis presents the influence of the selected parameters on the considered engineering properties including the compressive strength, flexural strength and the modulus of elasticity of rubberized concrete. In addition, it presents the development of predictive mathematical models on the basis of regression analysis and artificial neural network. Also, it estimates the most significance treatments on the constructed models.

4.2 Individual Treatments Influence

In this research, nine treatments which might influence the behavior of rubberized concrete are collected. The individual effect of each one of these treatments on the compressive strength, flexural strength and modulus of elasticity is presented as follows.

4.2.1 Influence of the Cement Mass Content Per Cubic Meters

Results indicated a direct relation between the cement content per cubic meters and the compressive strength of rubberized concrete. This can be clearly observed in Figure 5. While regarding tensile strength the increase in cement content shows a slightly increase in the tensile strength. This is shown in figure 6. On the other hand, the flexural strength of rubberized concrete is inversely related with the cement content. Since, the general behavior of flexural strength is reduced as the cement content in kilograms per cubic meters increases as illustrated in Figure 7. On the contrary, modulus of elasticity increases as the cement content per cubic meters increases which can be observed in Figure 8.

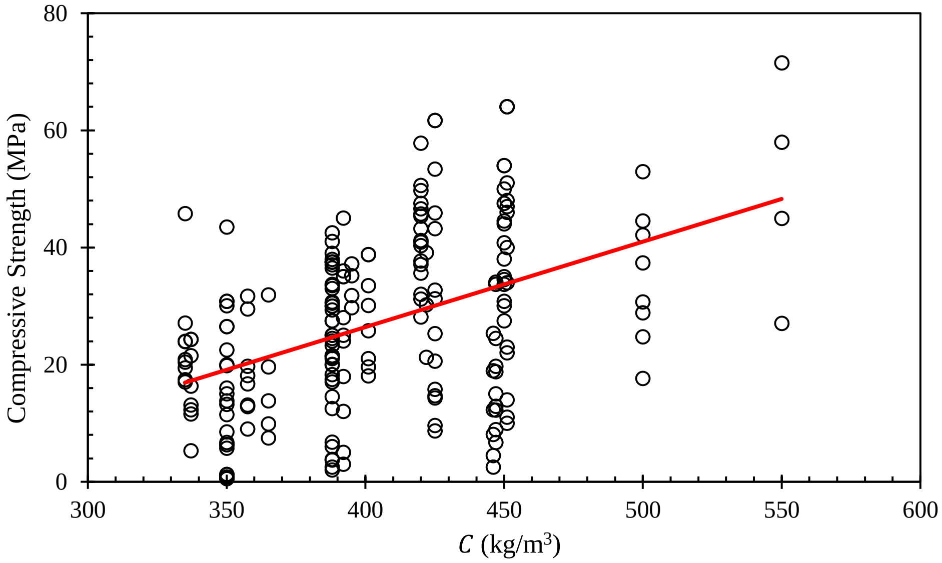

Figure 5: Influence of cement mass content per cubic meters on compressive strength.

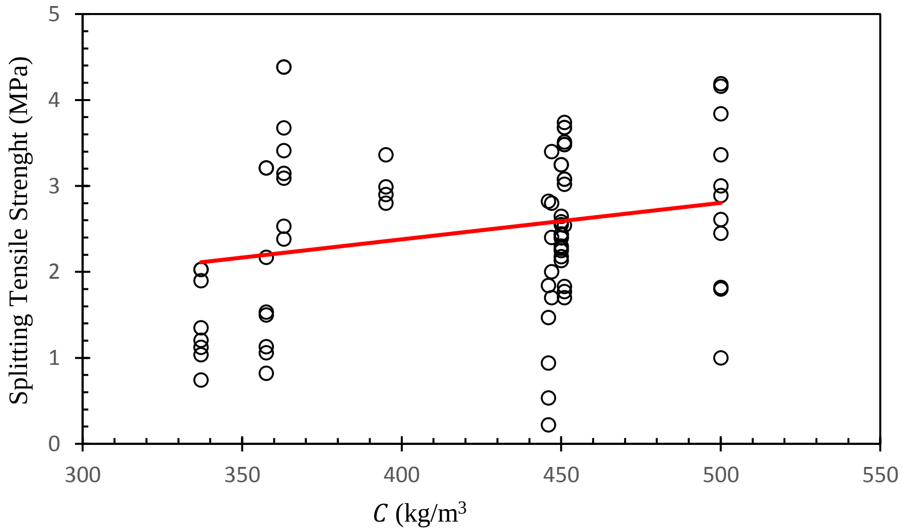

Figure 6: Influence of cement content on the splitting tensile strength.

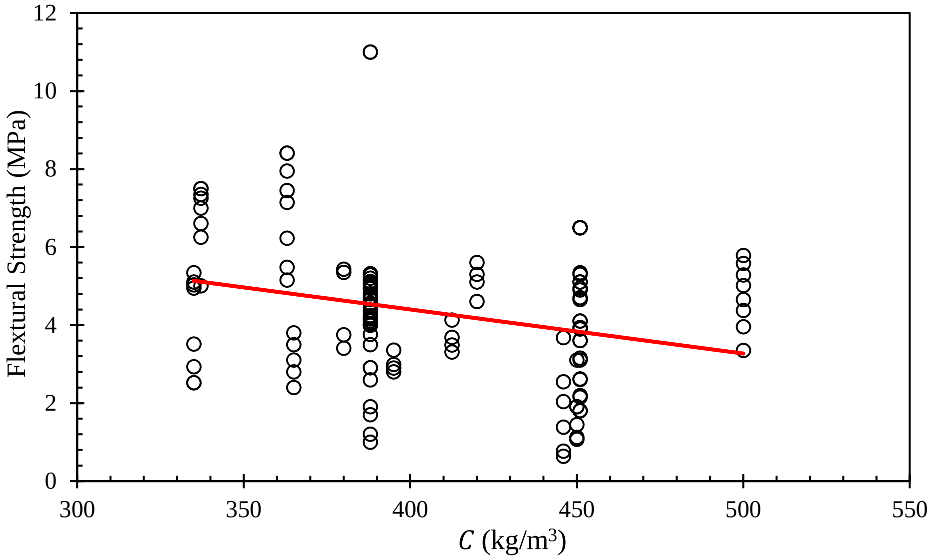

Figure 7: Influence of cement mass content per cubic meters on flexural strength.

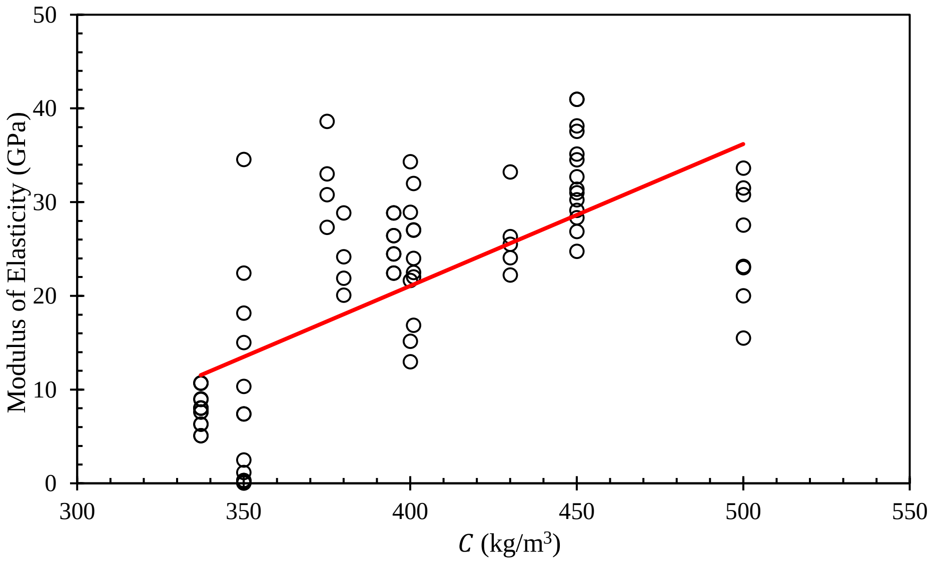

Figure 8: Influence of cement mass content per cubic meters on elasticity modulus.

4.2.2 Influence of the Water Mass Content per Cubic Meters

The developed compressive strength is dramatically reduced as the water content by mass is increased as presented in Figure 9. Also Figure 10 shows a dramatically reduction in splitting tensile strength as the water content increases. But there are no relations seams to exist between the flexural strength and the water content by mass as shown in Figure 11. On the other hand, the modulus of elasticity of rubberized concrete is inversely proportional to water content by mass in cubic meters of the fresh mixed concrete which can be clearly observed in Figure 12.

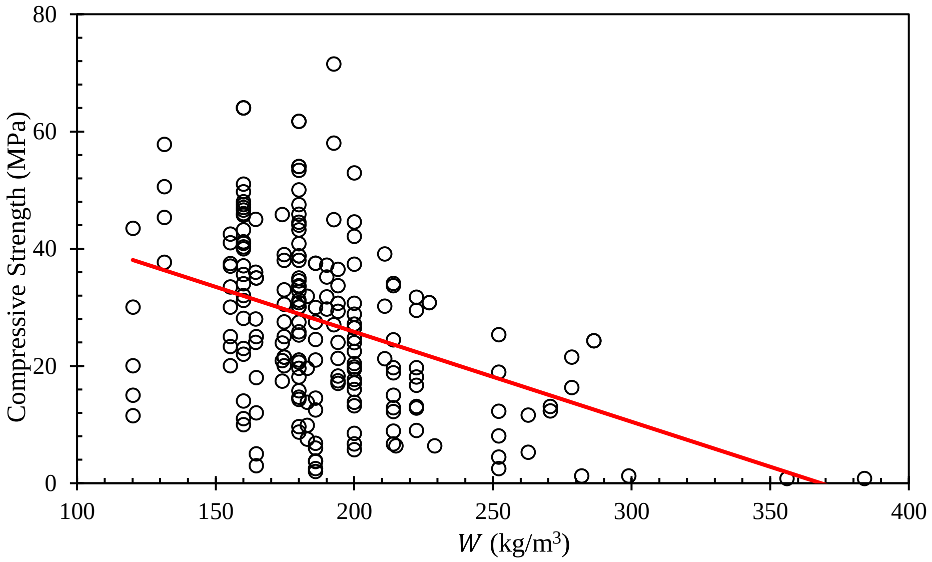

Figure 9: Influence of water content on the compressive strength.

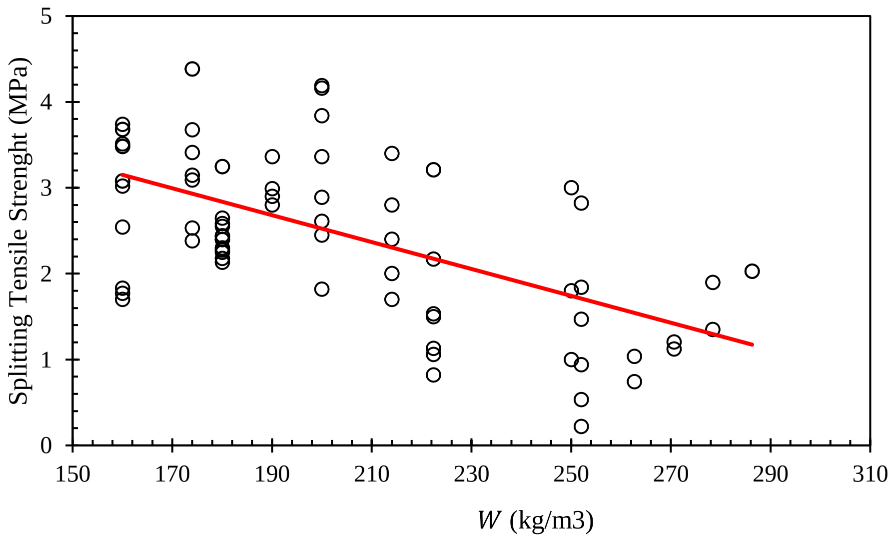

Figure 10: Influence of water content on the splitting tensile strength.

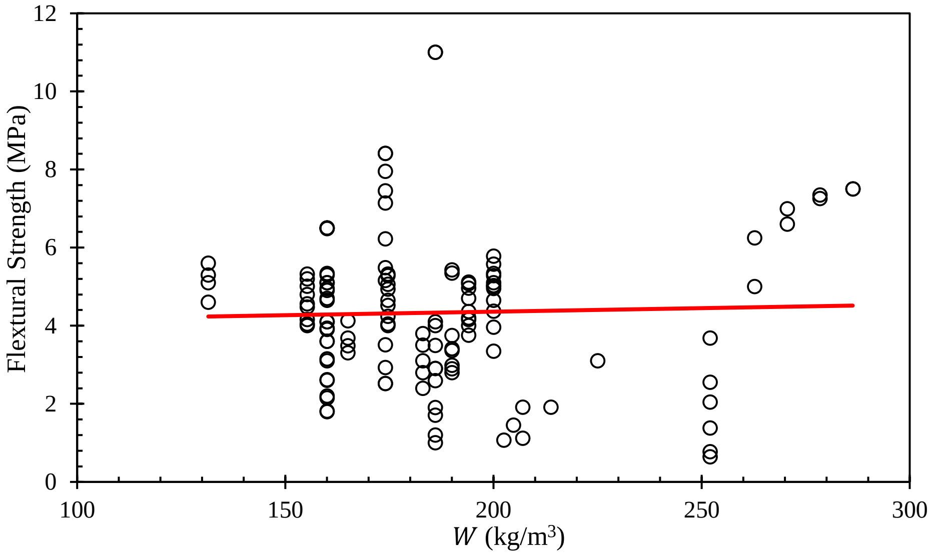

Figure 11: Influence of water content on the flexural strength.

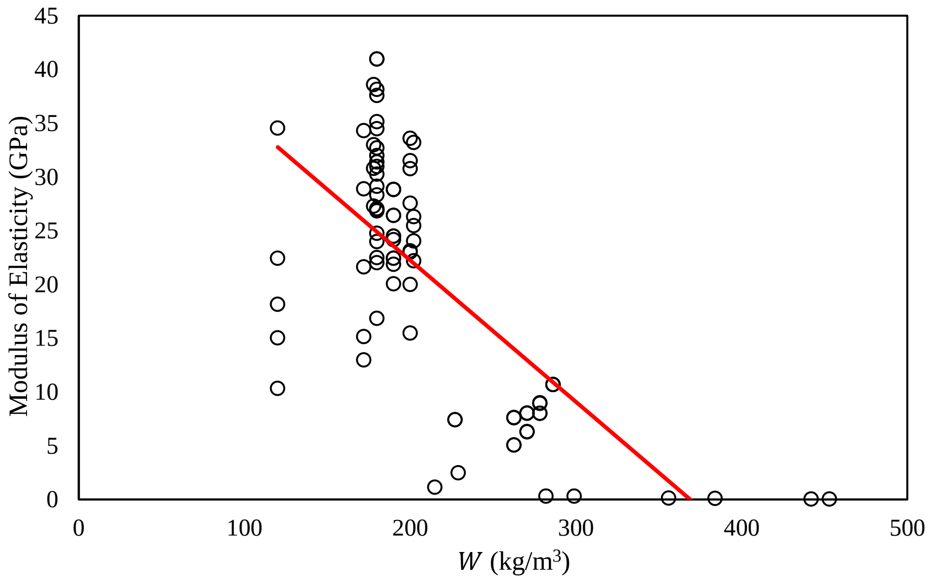

Figure 12: Influence of water content on the elasticity modulus.

4.2.3 Influence of the Coarse Aggregate Mass Content Per Cubic Meters

All of compressive strength, splitting tensile strength, Flexural strength and modulus of elasticity of rubberized concrete are positively influenced by the coarse aggregate content per cubic meter of the fresh rubberized concrete mix. As the content increases all the consider engineering property of the rubberized concrete increases in return as presented in Figure 13 -16.

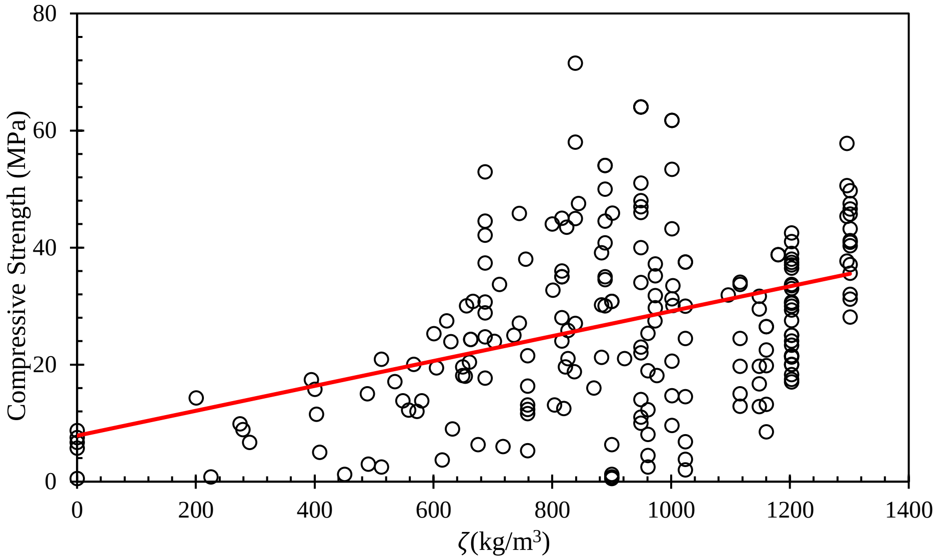

Figure 13: Influence of coarse aggregate content on the compressive strength.

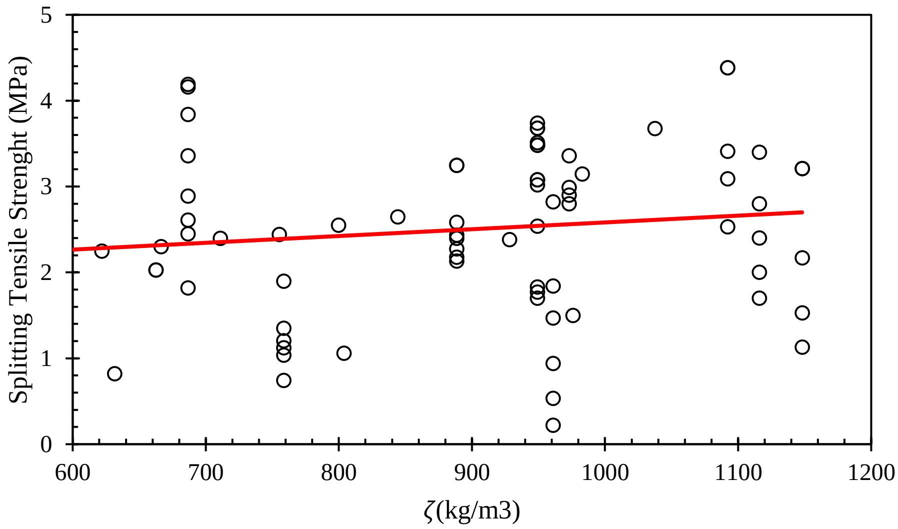

Figure 14: Influence of coarse aggregate content on the splitting tensile strength.

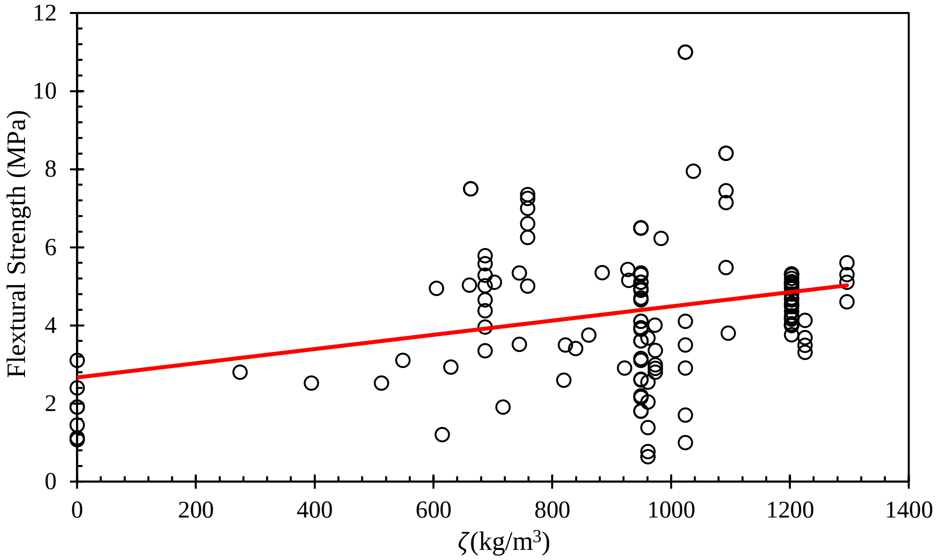

Figure 15: Influence of coarse aggregate content on the flexural strength.

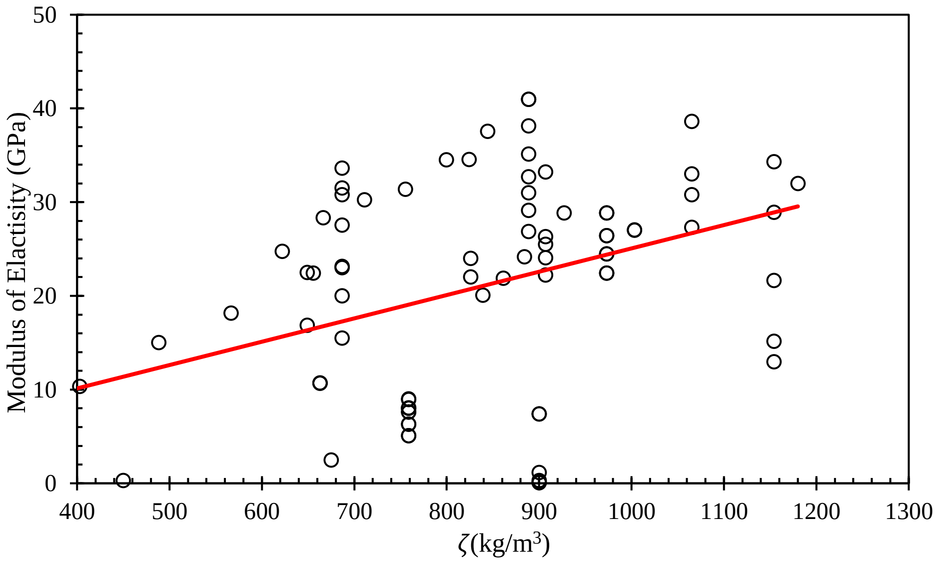

Figure 16: Influence of coarse aggregate content on the elasticity modulus.

4.2.4 Influence of the Fine Aggregate Mass Content Per Cubic Meters

The results presented in Figure 17show that the compressive strength of rubberized concrete increases as the fine content by mass increases. The same applies to splitting tensile strength Figure 18 On the other hand, the flexural strength seems to be independent of the fine content by mass as no relation seems to exist between the collected data as displayed in Figure 19 Ultimately, the modulus of elasticity is dependent of the fine content unlike the flexural strength as shown in Figure 20 where the modulus of elasticity increases as the fine content increases.

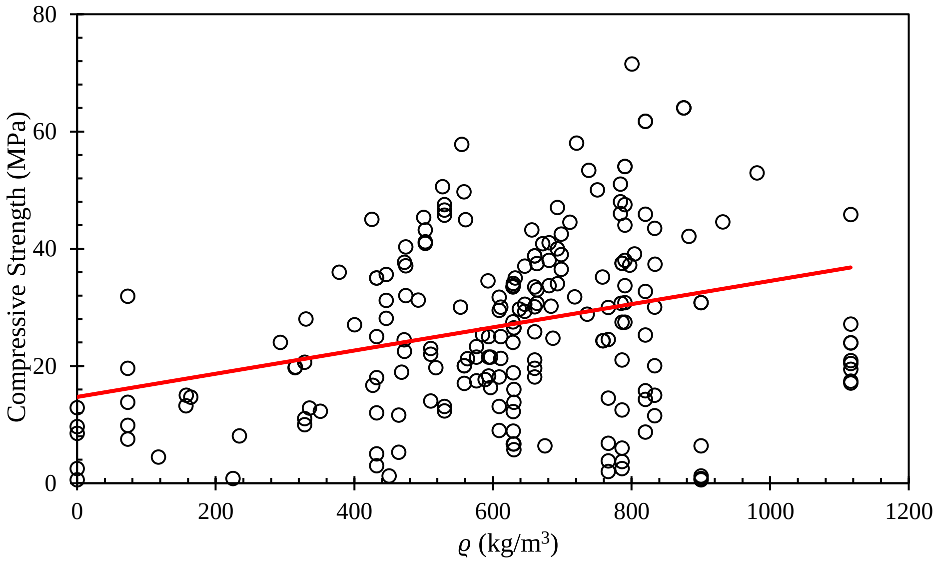

Figure 17: Influence of fine aggregate content on the compressive strength.

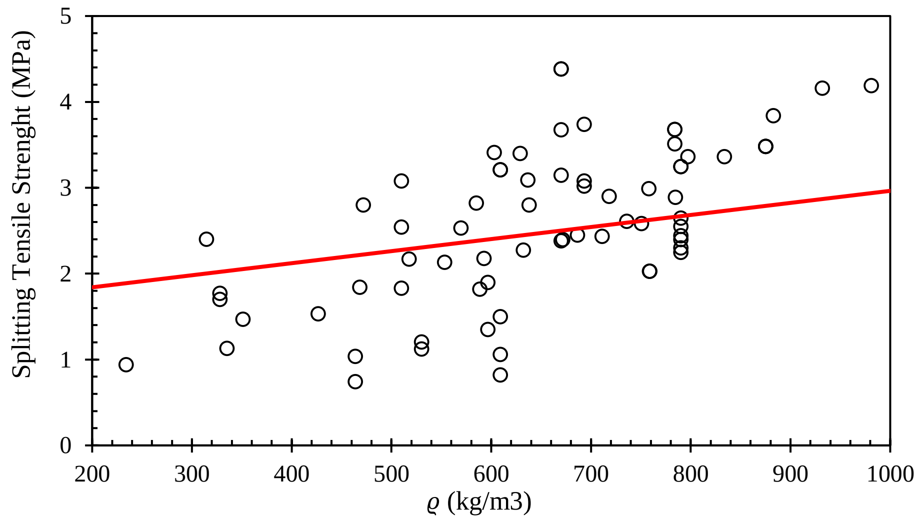

Figure 18: Influence of fine aggregate content on the splitting tensile strength.

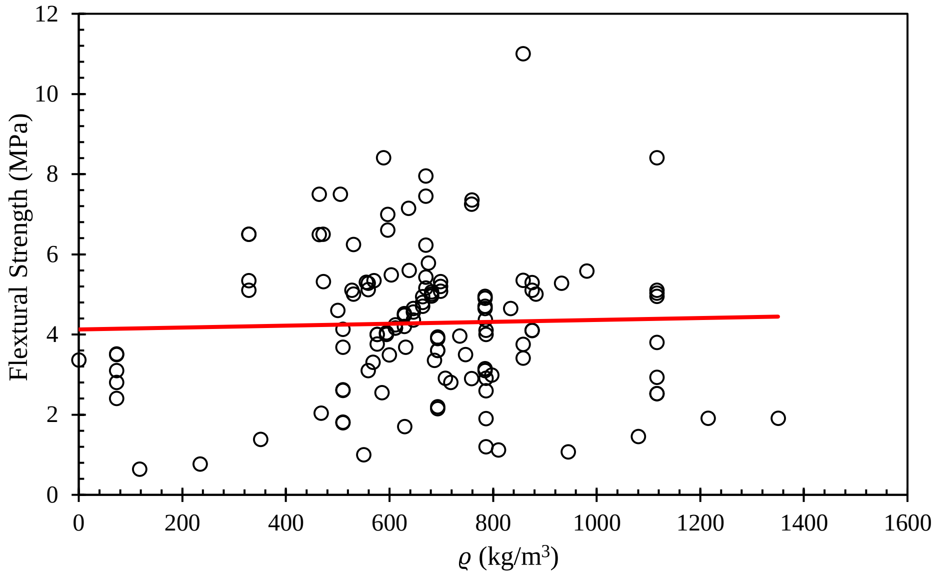

Figure 19: Influence of fine aggregate content on the flexural strength.

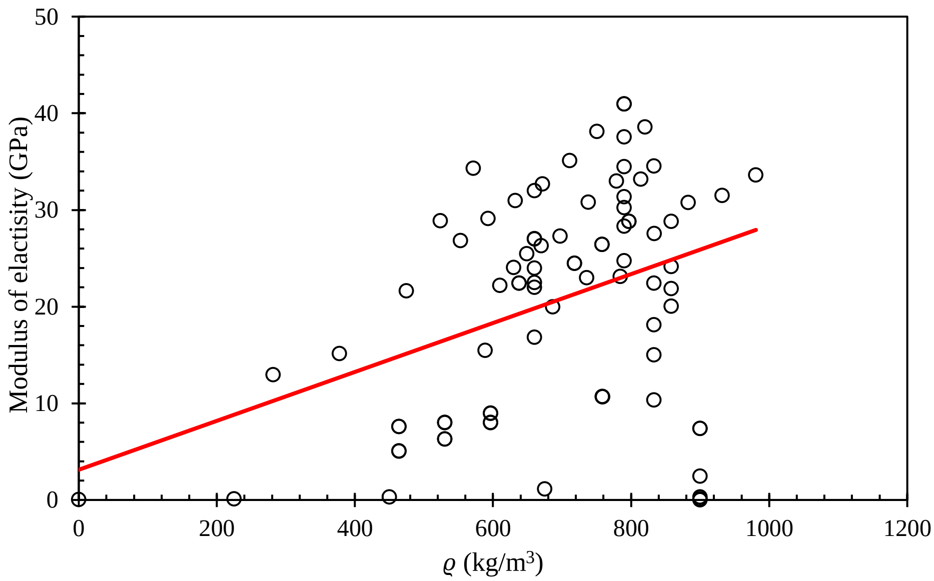

Figure 20: Influence of fine aggregate content on the elasticity modulus.

4.2.5 Influence of the Water Cement Ratio

The relation between the compressive strength of rubberized concrete and the water cement ratio is inversely proportional as the compressive strength is reduced upon increasing the water cement ratio which is clearly observed in Figure 21. This reduction is also can be observed in splitting tensile strength, Figure 22, on the contrary, the flexural strength is unaffected by the water cement ratio where no relation appears to exist as presented in Figure 23. on the other hand, modulus of elasticity is reducing as the water cement ratio increases which can be observed in Figure 24.

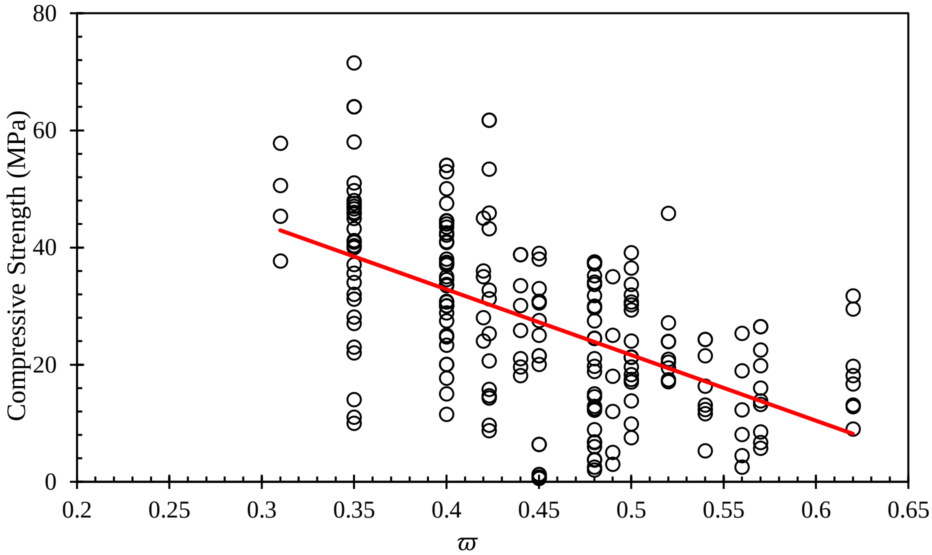

Figure 21: Influence of water cement ratio on compressive strength.

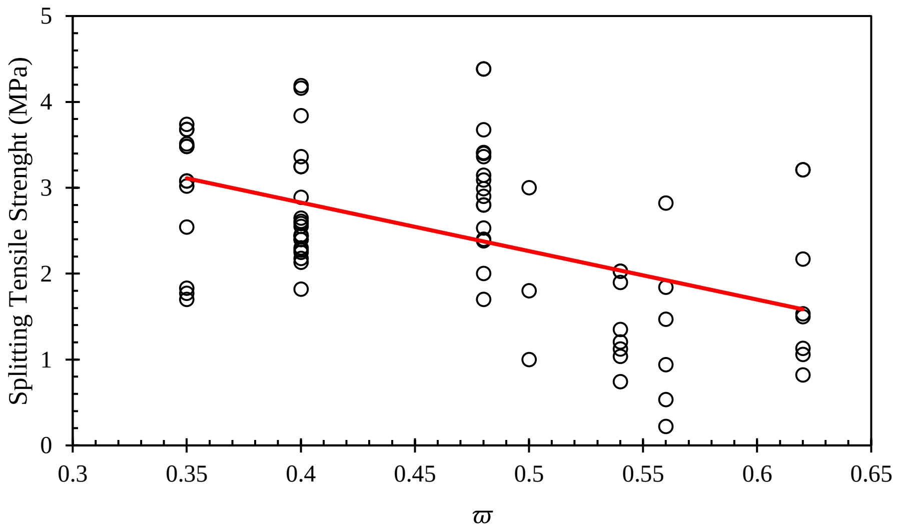

Figure 22: Influence of water cement ratio on splitting tensile strength.

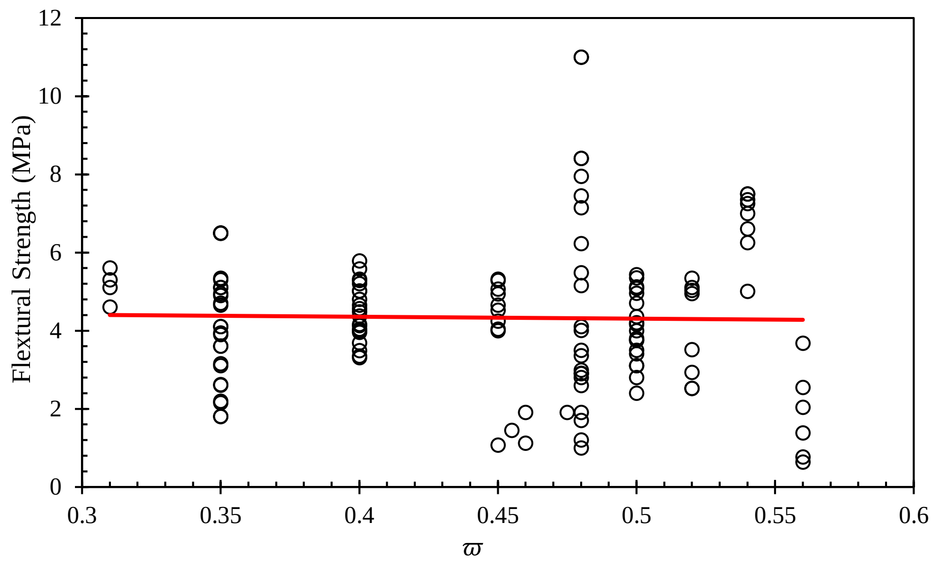

Figure 23: Influence of water cement ratio on flexural strength.

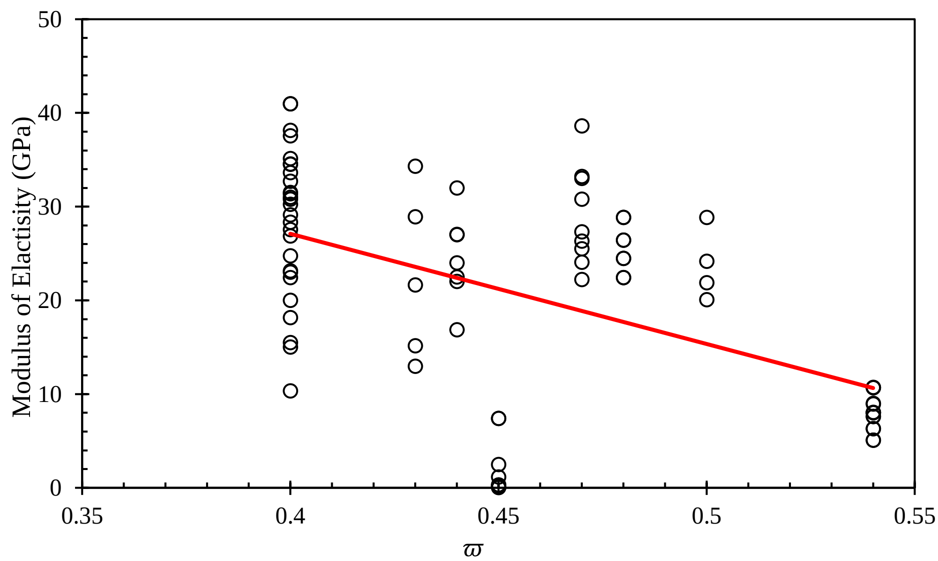

Figure 24: Influence of water cement ratio on the modulus of elasticity.

4.2.6 Influence of the Rubber Replacement Percentage

All of the considered engineering properties of rubberized concrete are reduced upon increasing the rubber replacement percentage with aggregate. Which emphasize that rubber has negative effect on the strength properties such as the compressive strength, flexural strength and the modulus of elasticity which is clearly observed in the Figure 25 -28.

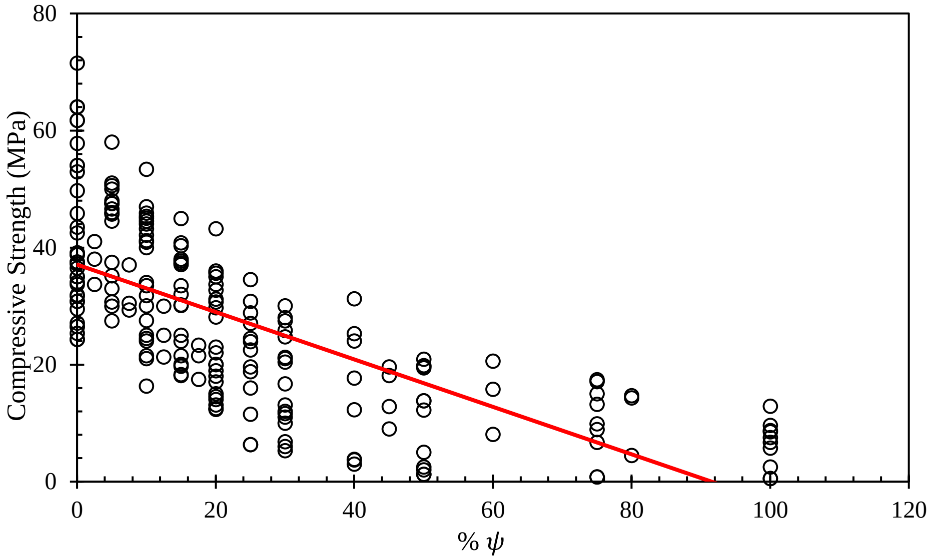

Figure 25: Influence of rubber replacement percentage on compressive strength.

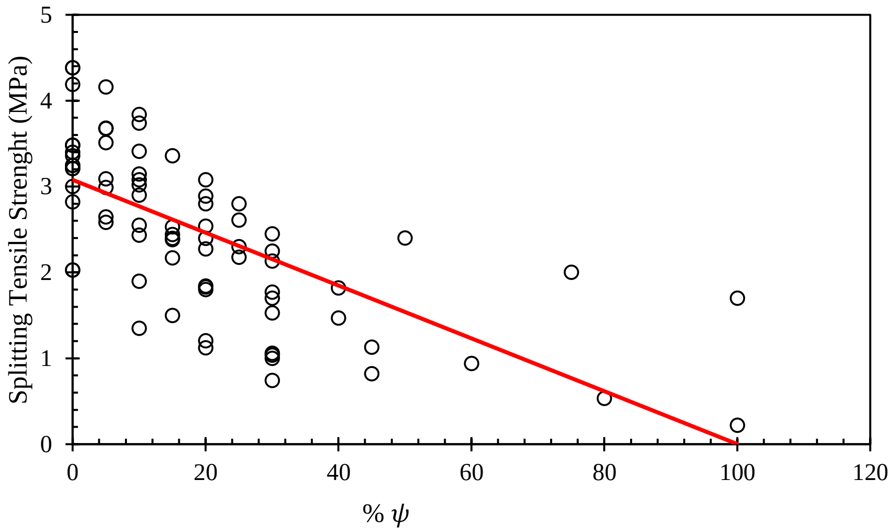

Figure 26: Influence of rubber replacement percentage on splitting tensile strength.

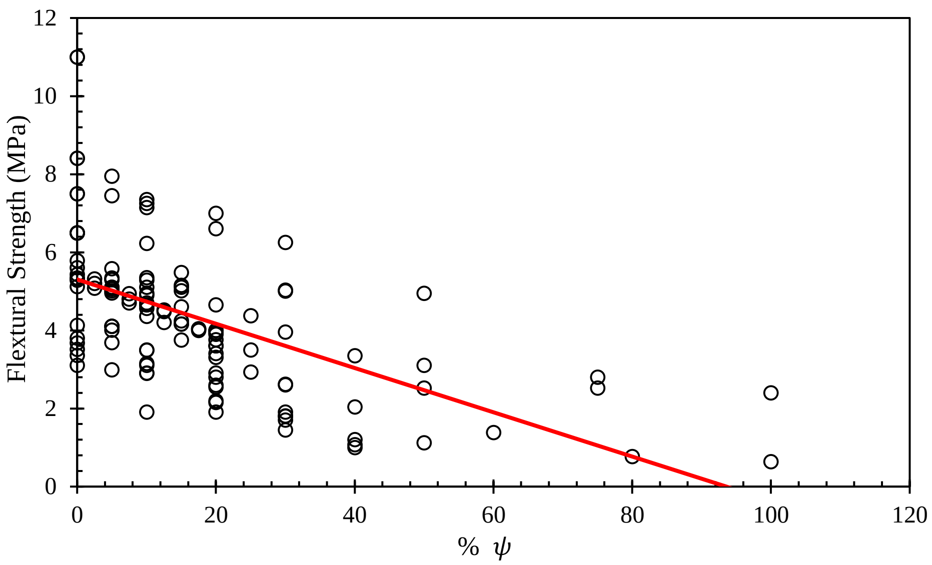

Figure 27: Influence of rubber replacement percentage on flexural strength.

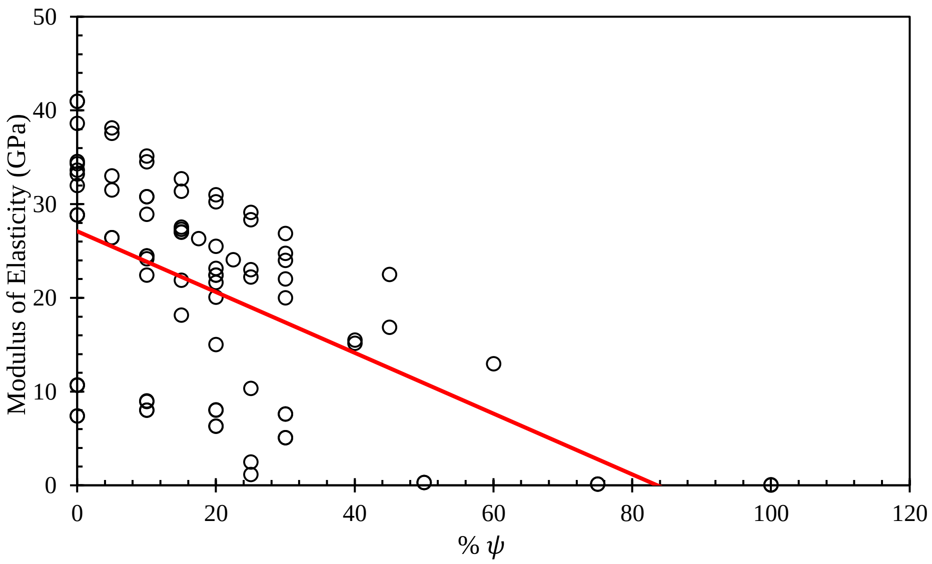

Figure 28: Influence of rubber replacement percentage on elasticity modulus.

4.2.7 Influence of the Rubber Mass in Cubic Meters

The rubber mass in the fresh rubberized concrete mix significantly reduced the development of the strength property such as compressive strength, flexural strength and modulus of elasticity since it replaces the mass of the stronger particles of aggregate. This can be clearly observed in the Figure 29 - 32.

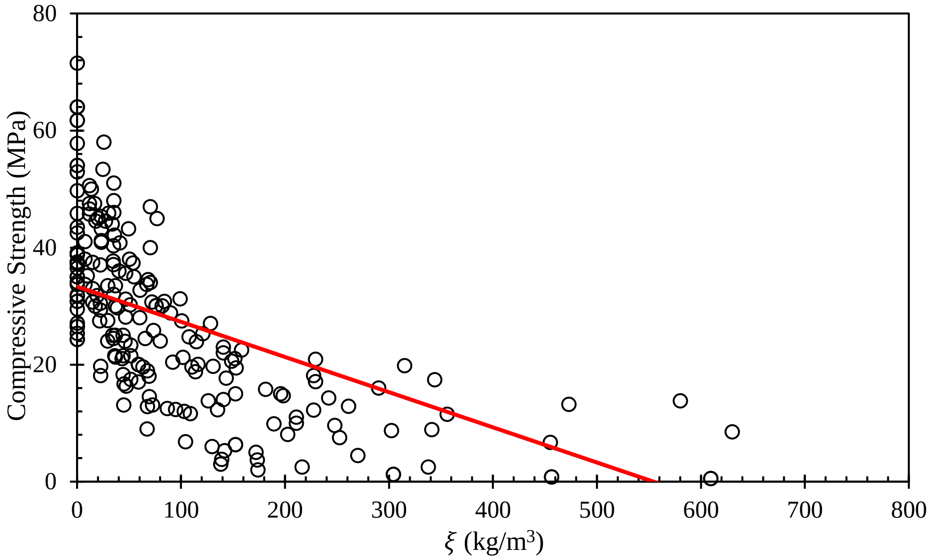

Figure 29: Influence of rubber mass in cubic meters on compressive strength.

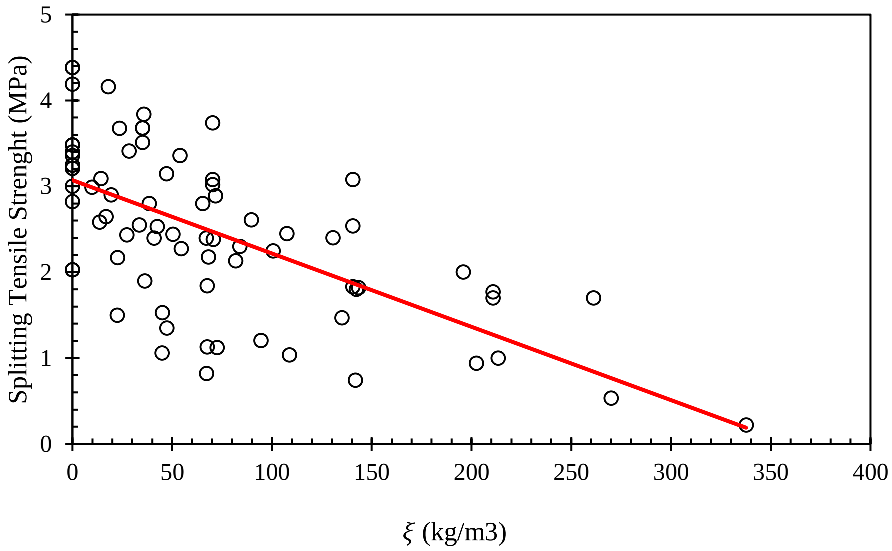

Figure 30: Influence of rubber mass in cubic meters on splitting tensile strength.

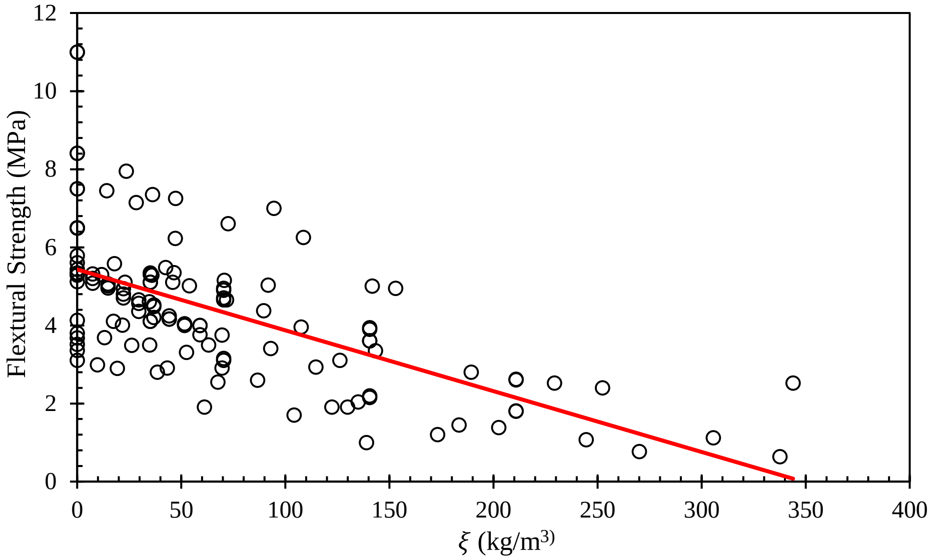

Figure 31: Influence of rubber mass in cubic meters on flexural strength.

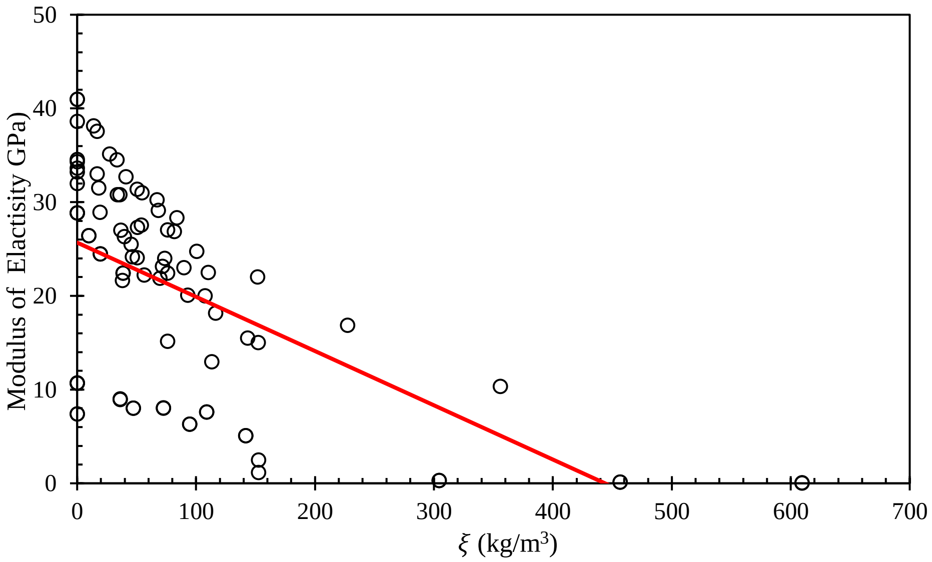

Figure 32: Influence of rubber mass in cubic meters on elasticity modulus.

4.2.8 Influence of the Maximum Size of the Used Rubber

The results presented in Figure 33 and Figure 35 shows that the maximum size of the used rubber slightly reduced the compressive strength, and the flexural strength of rubberized concrete. On the other hand, splitting tensile strength and modulus of elasticity is independent of the maximum used rubber size as no relation seems to exist as presented in Figure 34 and Figure 36.

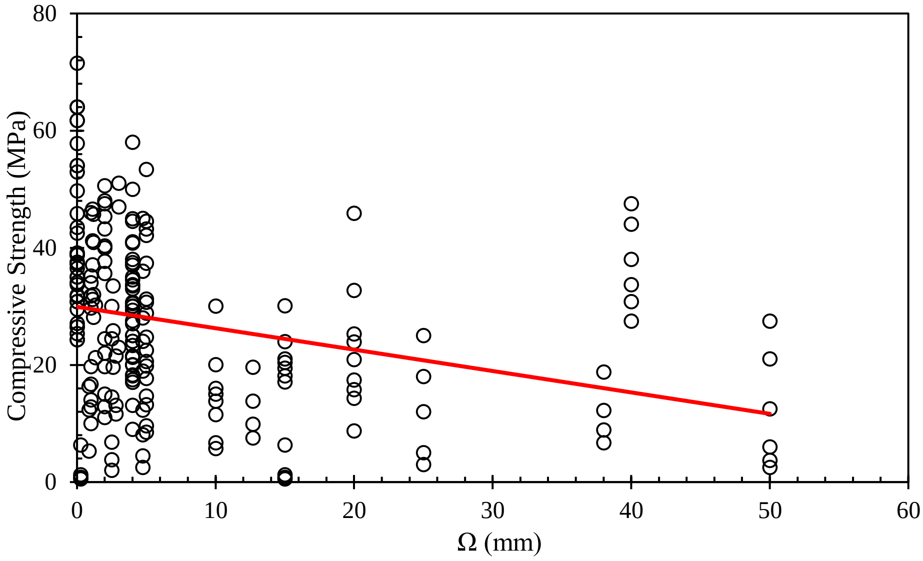

Figure 33: Influence of maximum size of the used rubber on compressive strength.

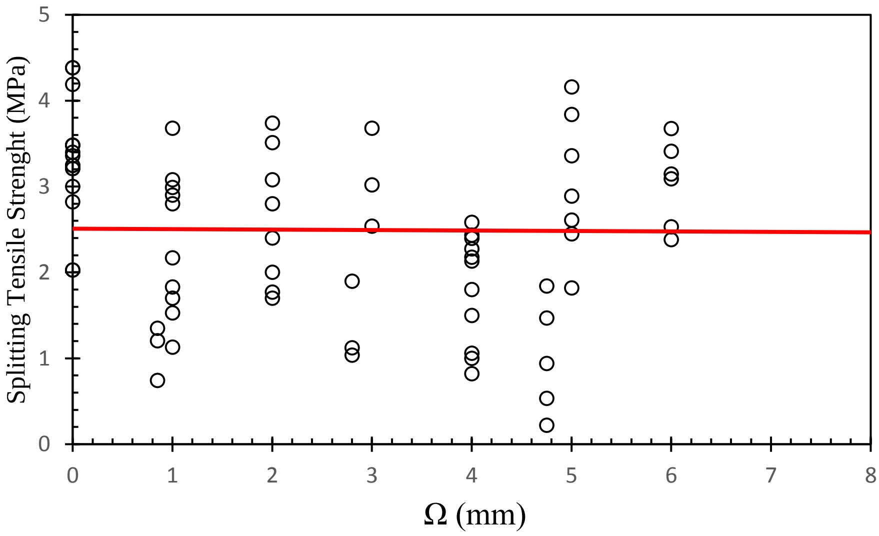

Figure 34: Influence of maximum size of the used rubber on splitting tensile strength.

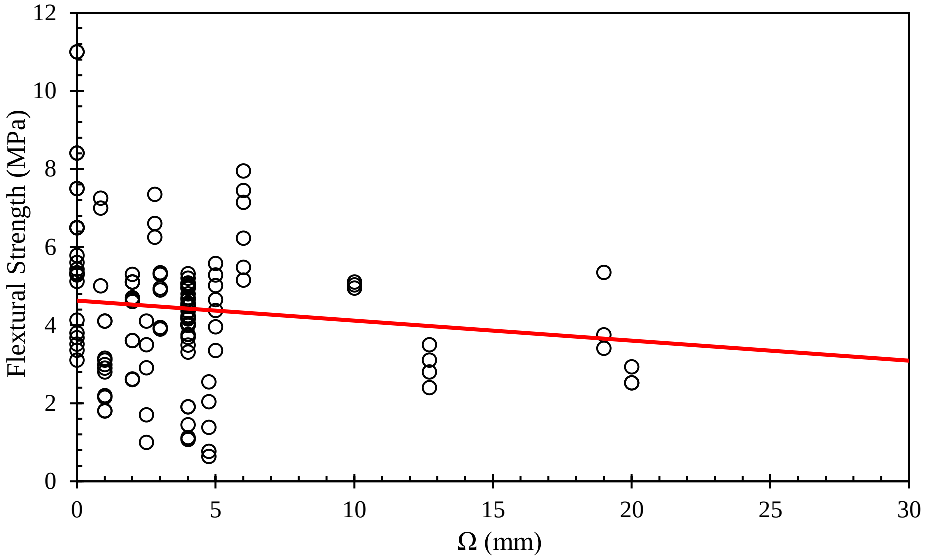

Figure 35: Influence of maximum size of the used rubber on flexural strength.

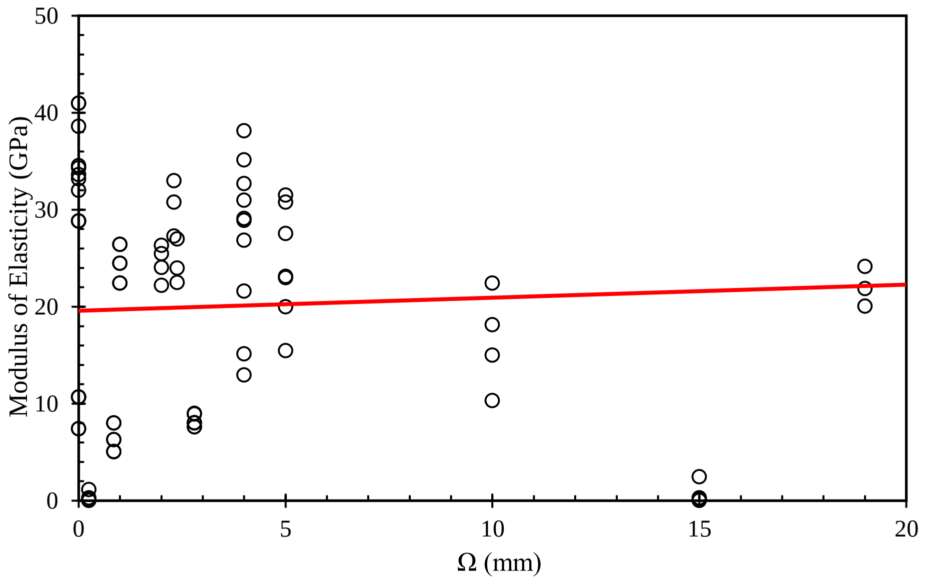

Figure 36: Influence of maximum size of the used rubber on elasticity modulus.

4.3 Regression Analysis

The regression analysis is a very common method in assessing and predicting the effect of multivariable treatments for a given output as highlighted in the second chapter. In this research, regression analysis is conducted in order to predict the engineering properties of rubberized concrete including the compressive strength, flexural strength, and modulus of elasticity. In the figures below, the black line is referred to the identity line, as a reference to the red line which referred to the multi linear regression analysis trend line.

4.3.1 Compressive Strength

Multivariable regression analysis which has been presented in chapter 3 shows moderate performance in predicting the compressive strength of rubberized concrete as illustrated in Figure 37. The coefficient of determination R^2 has a magnitude of 70%. The regression analysis overestimates the obtained compressive strength at low compressive stresses and underestimates the high stresses. This might be due to the nonlinear behavior between the selected treatments and the obtained compressive strength. The regression equation is presented in Equation 4.1.

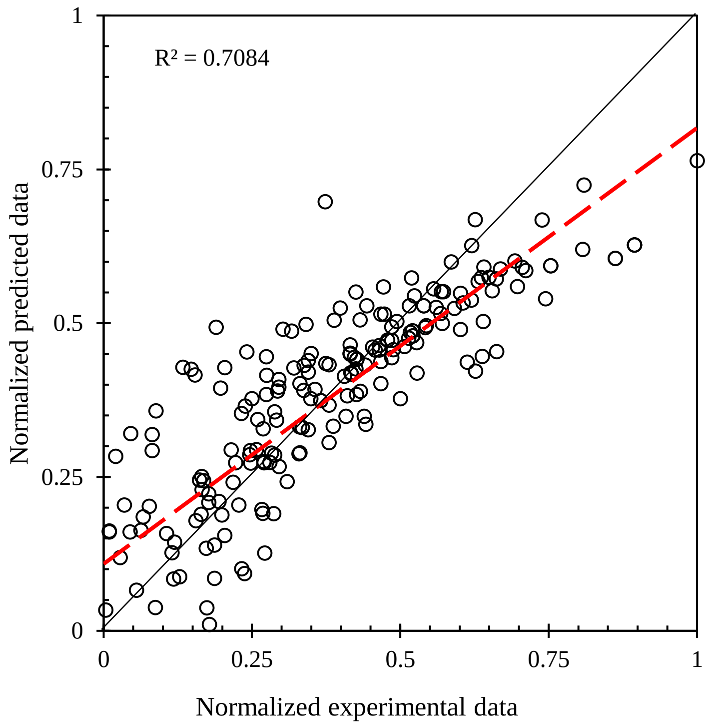

Figure 37: Compressive strength regression analysis results.

$$F_c = 0.25\ C_i - 0.15W_i + 0.06\zeta_i + 0.18\varrho_i + 0.12\varpi_i + 0.15\varsigma_i - 0.38\psi_i + 0.02\xi_i - 0.15\Omega_i + 0.34 \quad (4.1)$$

where F_c: represents the compressive strength of rubberized concrete.

4.3.2 Splitting Tensile Strength

The regression analysis shows a good prediction of splitting tensile strength of the rubberized concrete, where Figure 38 illustrates the general behavior of the predicted data versus the actual data. The coefficient of determination R^2 has a magnitude of 78%. The regression analysis overestimates the obtained splitting tensile strength at low splitting tensile stresses and underestimates the high stresses. This might be due to the nonlinear behavior between the selected treatments and the obtained compressive strength. The regression equation is presented in Equation 4.2.

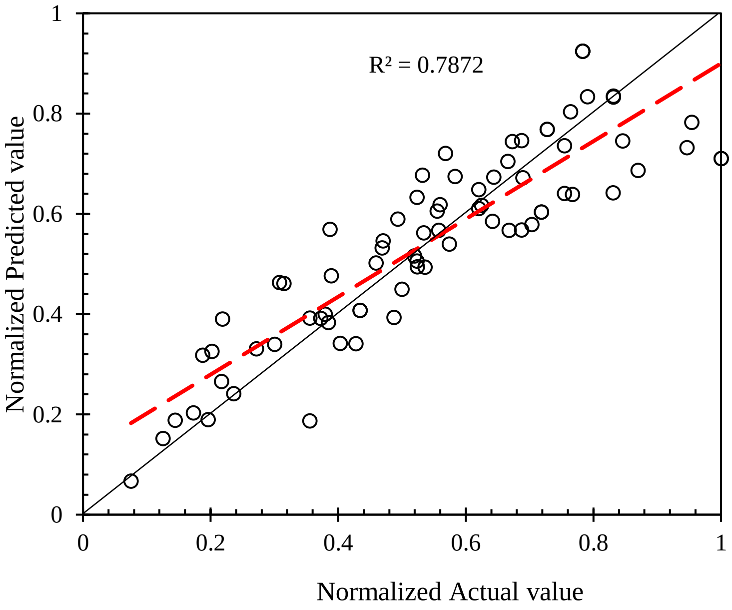

Figure 38: Splitting tensile strength regression analysis results.

$$F_T = 0.1831C_i + 0.015W_i + 0.0765\zeta_i + 0.845\varrho_i - 0.0805\varsigma_i + 0.215\varpi_i - 0.027\psi_i - 0.401\xi_i - 0.0376\Omega_i - 0.298 \quad (4.2)$$

where, F_T: is the Splitting Tensile strength of the rubberized concrete

4.3.3 Flexural Strength

The regression analysis poorly predicted the flexural strength of rubberized concrete, where the general behavior of the plotted predicted data versus the actual data seems to be more scattered and the coefficient of determination has a decent value of roughly R^2 =55%. Generally, the regression analysis overemphasizes the flexural strength at its lowest values and underrates the flexural strength at its higher magnitudes as presented in Figure 39. The regression equation is presented in Equation 4.3.

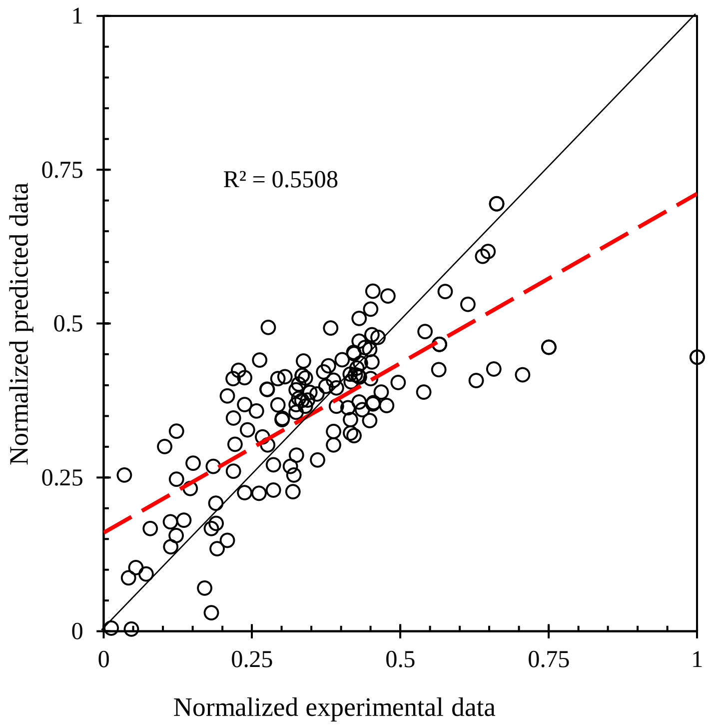

Figure 39: Flexural strength regression analysis results.

$$F_f = -0.33\,C_i + 0.35W_i + 0.01\zeta_i + 0.09\varrho_i - 0.31\varpi_i + 0.09\varsigma_i - 0.001\psi_i - 0.41\xi_i - 0.13\Omega_i + 0.572 \quad (4.3)$$

where, F_f: is the flexural strength of the rubberized concrete.

4.3.4 Modulus of Elasticity

The regression analysis for predicting modulus of elasticity as illustrated in Figure 40 indicates a good relation as the R^2 value is about 80% and the general behavior almost lay on the 1:1 ratio line which indicates that the multivariable regression analysis is neither overestimated nor underestimating the modulus of elasticity. Hence the author suggests that the implication of regression analysis in predicting modulus of elasticity is valid. The formula for the constructed regression analysis is presented in Equation 4.4.

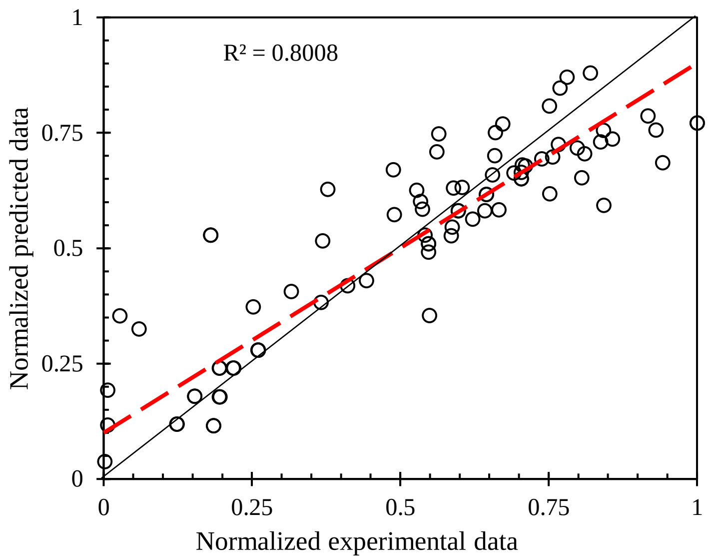

Figure 40: Modulus of elasticity regression analysis results.

$$E_c = 0.44\,C_i + 0.06W_i + 0.87\zeta_i + 0.51\varrho_i + 0.04\varpi_i + 0.29\varsigma_i - 0.33\psi_i + 0.11\xi_i + 0.05\Omega_i - 0.67 \quad (4.4)$$

where, E_c: is the modulus of elasticity of the rubberized concrete.

4.4 Artificial Neural Network

In the present day, the implication of artificial neural network is showing its significance in scientific world and is trending as a powerful tool for prediction models because of its higher accuracy as compared to the conventional methods. In this study, ANN model is constructed as presented in chapter 3 to estimate the engineering properties such as compressive strength, flexural strength and elastic modulus of rubberized concrete as discussed. In the figures below, the black line is referred to the identity line, as a reference to the red Artificial neural network regression analysis trend line.

4.4.1 Compressive Strength

The ANN model developed to predict the compressive strength as illustrated in Figure 41 shows higher accuracy indicating the implication of developed neural networks as the coefficient of determination is approximately 94%. Thus, the author suggests that the application of stated neural networks can be utilized to predict the compressive strength with very high accuracy for rubberized concrete.

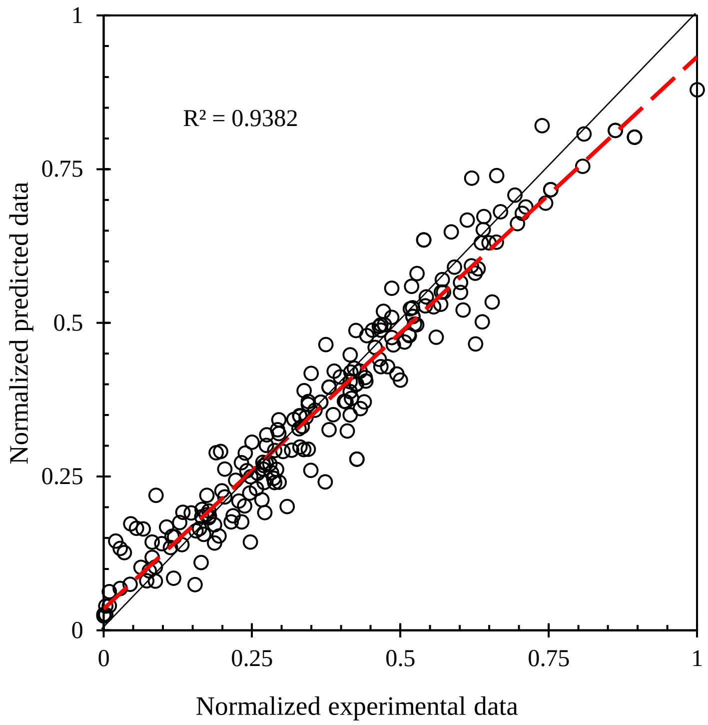

Figure 41: Compressive strength ANN model results.

4.4.2 Splitting Tensile Strength

The ANN model developed to predict the splitting tensile strength as shown in Figure 42 shows higher accuracy indicating the implication of developed neural networks as the coefficient of determination is approximately 93%. Thus, the author suggests that the application of stated neural networks can be applied to predict the splitting tensile strength with very high accuracy for rubberized concrete.

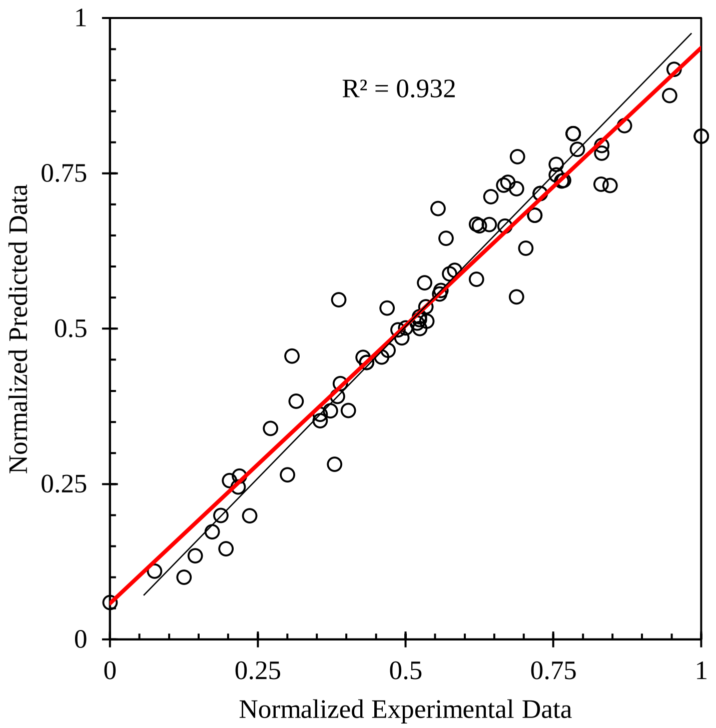

Figure 42: Splitting tensile strength ANN model results.

4.4.3 Flexural Strength

Similarly, for flexural strength, the ANN model also shows a higher accuracy as the R^2 value is approximately 83% as shown in Figure 43. However, it is worth to mention that at quarter range the measured flexural strength shows a scatter trend which might be due to minor materials divergence during experimental work since it did not influence the general behavior of the constructed ANN model.

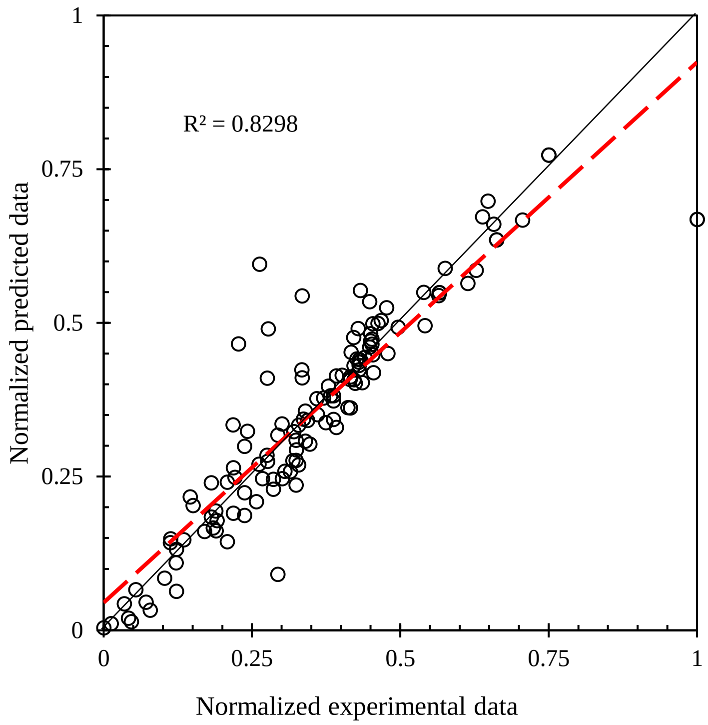

Figure 43: Flexural strength ANN model results.

4.4.4 Modulus of Elasticity

In brief, the ANN model for elastic modulus is shown approximately identical behavior as illustrated in Figure 44 where the coefficient of determination is 97% thus indicating applicability of the constructed mathematical model with high accuracy.

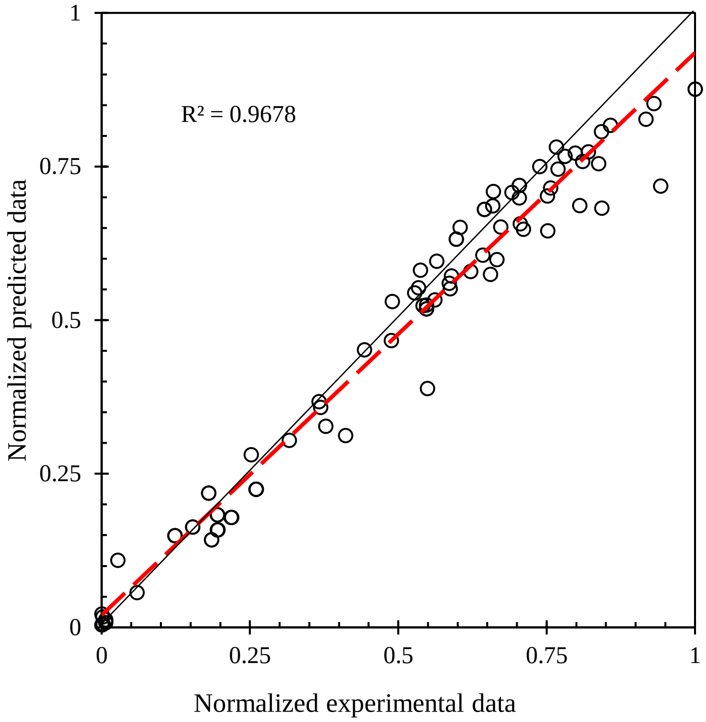

Figure 44: Elastic modulus ANN model results.

4.5 Comparison between the Constructed Mathematical Predictive Models

The results presented in Table 7 illustrated that artificial neural network is superior in predicting the engineering properties of rubberized concrete since it has a coefficient of determination as close to one as possible unlike the regression analysis where it is rather possessing a moderate regression coefficient. Although ANN uses only 70 percent of the data where the regression analysis uses all the obtained data. In addition, ANN had higher accuracy in predicting the elasticity modulus with almost exact approximation.

Table 7: Comparison of the developed mathematical model on the basis of R^2

Properties	Regression analysis R^2	ANN R^2
Compressive strength	0.7084	0.9382
Splitting Tensile Strength	0.7872	0.93
Flexural strength	0.5508	0.8298
Elasticity modulus	0.8008	0.9678

4.6 Significance Parameters

Various input parameters are used in constructing the mathematical predictive model. However, not all of which have the same influence on the obtained results. This part of the study highlights the significance predictive parameters based on various methods.

4.6.1 Compressive Strength

All the conducted methods in sorting the significance parameters on the constructed models shows that the rubber replacement percentage and cement content by mass in the cubic meter and the fine aggregates content. of the fresh rubberized concrete have the highest significance. On the contrary, the least significant parameters are rubber and coarse aggregate masses in the fresh concrete mix. The detailed order of the influencing parameters is presented in Table 8. The percentage of rubber have the most effect on the compressive strength of rubberized concrete, the reason behind this is the crack initiation that have the same pattern for the crack formed by the air voids, this crack formed due to the deformability of the rubber particles relative to the cement microstructure that surround the rubber. Another reason that makes the percentage of rubber have the most significant effect on the compressive strength is the weak bond that formed between the cement paste and rubber surface due to hydrophobic natural of rubber and low absorbing property of rubber particles.

Table 8: Significant compressive strength predictive parameters influence order

Significance order	Standardized coefficient	P-Value
1st	ψ	ψ
2nd	C	C
3rd	ϱ	ϱ
4th	Ω	Ω
5th	ϖ	ς
6th	ς	ϖ
7th	W	W
8th	ζ	ζ
9th	ξ	ξ

4.6.2 Splitting Tensile Strength

In terms of the flexural strength of rubberized concrete, the significant parameters which influences the predictive output of the constructed model is highly influenced by cement content, fine and coarse content and rubber mass in fresh concrete mixture. Whereas, among the least influential parameters rubber replacement percentage, amount of water and rubber size are obtained that can be obviously observed in table 9. Several reasons for this phenomenon were previously provided by the researchers, the rubberized aggregates when it comes in content with cement paste acts as a cavity and creates a microcrack, thus a weak ITZ and stress concentration along the interfacial transition zone, this contribute and causes a rapid failure of the rubberized concrete under the tensile stress, replacing rubber to fine aggregates and coarse aggregates mainly reduce the splitting tensile strength.

Table 9: Significant splitting tensile predictive parameters influence order

Significance order	Standardized coefficient	P-Value
1st	ϱ	ς
2nd	ς	ϱ
3rd	ξ	ξ
4th	ϖ	C
5th	C	ϖ
6th	ς	ς
7th	Ω	Ω
8th	ψ	ψ
9th	W	W

4.6.3 Flexural Strength

In terms of the flexural strength of rubberized concrete, the significant parameters which influences the predictive output of the constructed model is highly influenced by cement content, water content and rubber mass in fresh concrete mixture. Whereas, among the least influential parameters rubber replacement percentage, coarse and fine aggregate are obtained which can be clearly observed in table 10. The decreasing in flexural strength is nearly similar to that of compressive and tensile strength, but the advantage of using rubber is that rubberized concrete does not fail suddenly under bending as normal concrete, rubberized concrete shows ductile failure. The weak bond between rubber and cement paste cause significant reduction in flexural strength.

Table 10: Significant flexural strength predictive parameters influence order

Significance order	Standardized coefficient	P-Value
1st	ξ	C
2nd	C	W
3rd	W	ξ
4th	ϖ	ϖ
5th	Ω	Ω
6th	ς	ς
7th	ϱ	ϱ
8th	ζ	ζ

9th	ψ	ψ

4.6.4 Elasticity Modulus

The mathematical model developed to predict the elastic modulus is extremely influenced by cement, coarse and fine aggregate masses content in the cubic meters of the fresh rubberized concrete mixture. On the other hand, water and water cement ratio has the least effect as illustrated in Table 11. Analysis illustrate that since amount of rubber replaced coarse and fine aggregates and the cement that is responsible for the bond between the cement paste and rubber, thus as explained above, the natural surface of rubber tends to repulse the cement paste. The static modulus of elasticity increases with the increase of rubber size and decreases with the increase of rubber content, as described in figure 36 and figure 32 respectively.

Table 11: Significant modulus of elasticity predictive parameters influence order

Significance order	Standardized coefficient	P-Value
1st	ζ	C
2nd	ϱ	ζ
3rd	C	ϱ
4th	ψ	ς
5th	ς	ψ
6th	ξ	Ω
7th	W	ξ
8th	Ω	ϖ
9th	ϖ	W

4.7 Influence of Rubber Content and Particle Size on the Compressive Strength of Concrete

Influence of rubber content and particle size, numerous studies reveals adverse impact on the concrete mechanical properties. The reduction in properties such as compressive, flexural and splitting tensile strength is directly proportional to several factors such as alteration in the uniformity of the particle gradation curve from well graded to poorly graded. Another aspect related to reduction is due to replacement of natural aggregates with flexible one's directing towards the weaker bond strength. This weaker bond strength is due to the development of porous medium in the interfacial transition zone (ITZ).

In Figure 45, the collected data for compressive strength were separated into fine rubber replaced fine aggregates, and coarse rubber replaced by coarse aggregates based on the size of rubber.

The results indicate that the reduction of compressive strength is directly linked to the increment in rubber particle size and this phenomenon is due to the larger formation of voids in the concrete matrix, Hence Generally and as shown in Figure 45, researchers suggest a higher optimum replacement level for fine aggregates than for coarse aggregates.

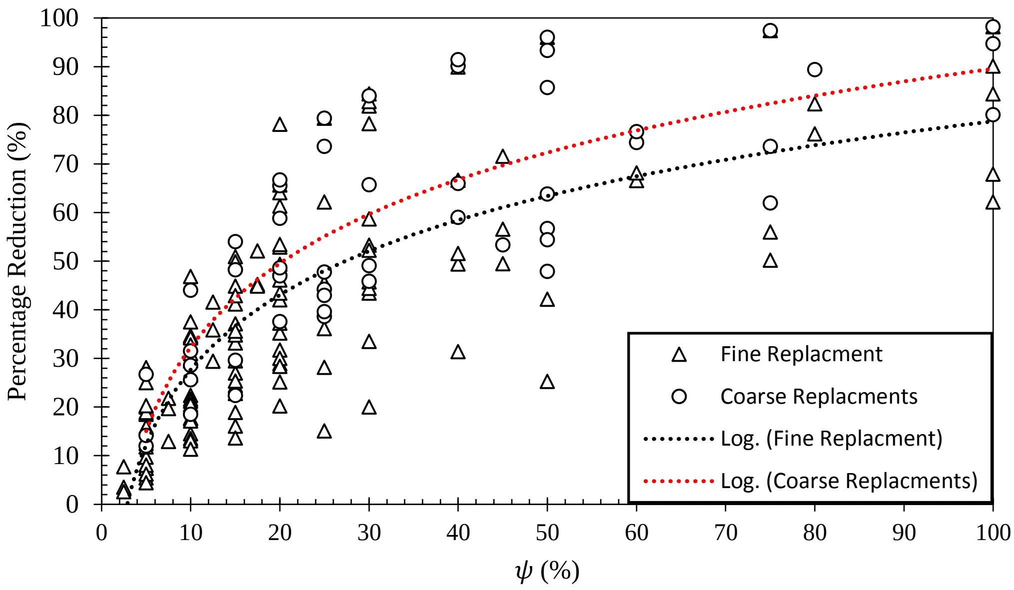

Figure 45: particle size and replacement percentage effect on compressive strength.

4.8 Correlation between Compressive Strength and Modulus of Elasticity

Previously, several concrete codes of practice including TS500 [75] and ACI318 [76] have proposed equations for predicting the modulus of elasticity using the concrete compressive strength. However, these equations were based on conventional concrete. Thus, in this study a new relation applicable for rubberized concrete is proposed based on the data of both control and different rubber replacement mixtures. As shown in Figure 46, the proposed Equation 4.5 provides a good linear fitting for the collected data from the literature with R^2 equals to 0.86.

$$E = 0.7826 f_c + 0.1795 \tag{4.5}$$

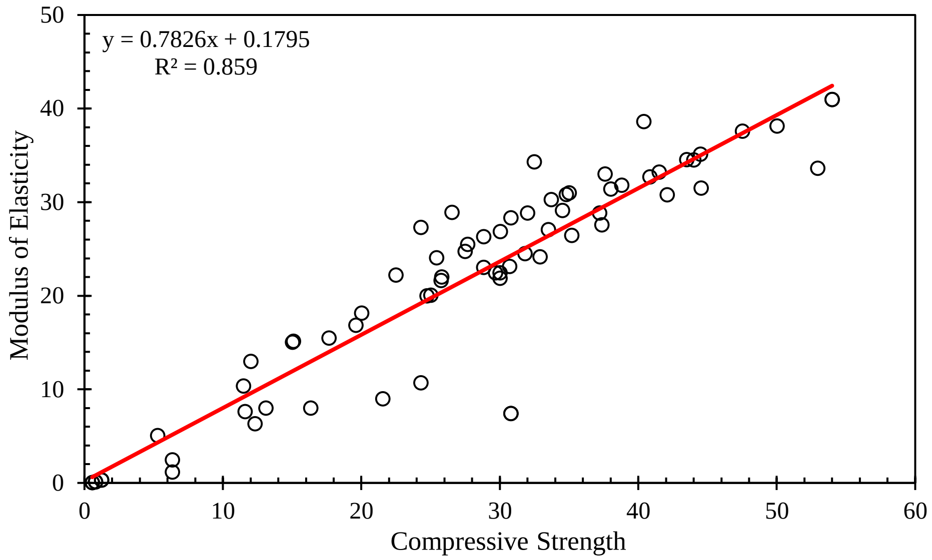

Figure 46: Elasticity modulus rubberized concrete verses compressive strength.

4.9 Correlation between Compressive Strength and Splitting Tensile Strength

In this study a new relation between compressive strength and splitting tensile strength applicable for rubberized concrete is proposed based on the data of both control and different rubber replacement mixtures. As shown in Figure 47, the proposed Equation 4.6 provides an acceptable linear fitting for the collected data from the literature with R^2 equals to 0.71.

$$f_T = 0.0507 f_c + 0.9049 \qquad (4.6)$$

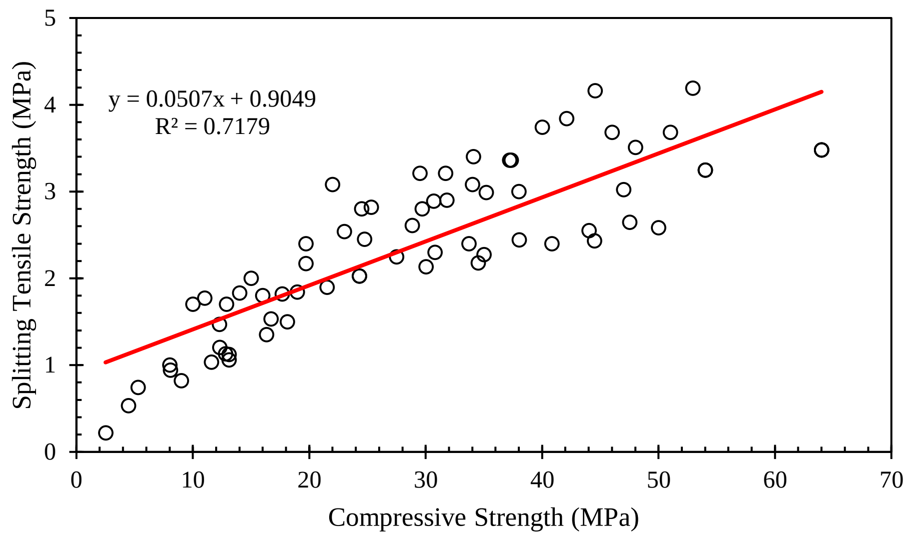

Figure 47: Splitting tensile strength against compressive strength.

4.10 Pre-treatment of Rubber Particles:

in order to increase the adhesion between rubber and cement paste, the pretreatment of rubber surface is needed thus resulting in strong interfacial transition zone and in the concrete matrix leads to remarkable improve. Several techniques where used where these techniques help in removing the zinc stearate film from rubber surface and increase its roughness result in improve in the bond strength between the cement paste and rubber aggregates. The pre-treatment of rubber aggregates by sodium hydroxide accelerate the cement hydration, and produces a weak basic condition along the rubber and cement interface, but after a specific time, rubber should be washed by water in order to reduce the pH of concrete. Since high pH can contribute in corrosion in the reinforced concrete. Figure (48) illustrate different kinds of treatments from different articles and shows the percentage of compressive strength relative to control when 20% replaced by volume of fine rubber were used, where these percentage seems to be suggested as the optimum replacement so after these percentage, rubber shows negative effects on the mechanical properties of the rubberized concrete. As shown in the figure (48) the treating of rubber with sodium hydroxide, showing a significant improvement in the compressive strength compared to the untreated rubber, and as its shown this kind of treatment is sensitive to the time and concentration of sodium hydroxide [77,78]. so as it shown soaking in 10% NaOH for 30 min has the less reduction in compressive strength with a percentage strength relative to control 82% [79], Precoating of rubber with cement powder show a small improve in the compressive strength with 68% strength relative to control [80]. While treating the rubber with a mixture of sodium hydroxide with silane coupling agent (SCA) and combined it with carboxlyated stryrene-butadiene rubber to modify the properties of rubber, it shows a considerable improvement in the compressive strength with a reduction of less than 5% compared to the control. The author suggests that this kind of treatment tends to the formation of hydrogen bonds and increase of van der Waal's forces between the treated rubber and the cement paste [82]. Heat treatment in different time ranges (1,1.5 and 2 hr) shows a reduction in compressive strength compared to untreated rubberized concrete with percentage of 51% [81]. Using the different chemicals (hydrogen peroxide, calcium chloride, sulfuric Acid, potassium permanganate & sodium bisulfate, polyvinyl alcohol, and acrylic acid and polyethylene glycol) to treat the rubber show a moderate significant improvement compared with the untreated rubberized concrete with a percentage of strength relative to control (66, 70, 66, 64, 85 & 63.8%) [79, 83, 84]. Treating of rubber using gamma radiation shows an improvement in the stiffing of the rubber particles with 66% strength relative to control [85] also soaking the rubber for 24 hours shows a small improve in the compressive strength with a 62% relative to control [86].

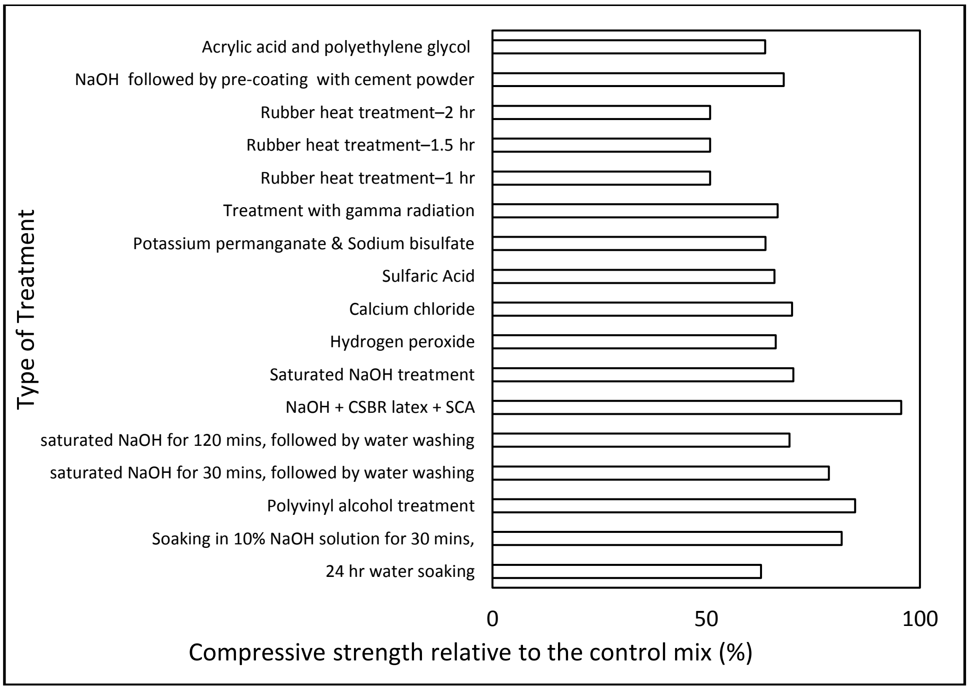

Figure 48: The percentage of compressive strength relative to control at different types of treatment.

Chapter 5

CONCLUSION

5.1 Conclusion

The aim of this study is to construct a mathematical predictive model to estimate the mechanical properties of rubberized concrete without the need to conduct any experimental work based on regression analysis and artificial neural network. Various conclusions are obtained which can be summarized in the following bullet points:

- The behavior of rubberized concrete is influenced by various factors of the initial concrete mixture, these factors include cement content, water content, mass of coarse aggregate, mass of fine aggregates, water-cement ratio, rubber content, size of rubber, percentage replacement by volume, and specific mass of rubber.
- Regression Analysis showed fair performance in predicting the engineering properties of rubberized concrete where the coefficient of determination ranged between 0.55 and 0.8 only where regression analysis either underestimate or overestimate the desired property.
- The constructed Artificial Neural Network model provided high accuracy in predicting the mechanical property of rubberized concrete with an accuracy of 96 percent.
- Replacement of sand by fine rubber particles is better that replacing coarse aggregates by coarse rubber in terms of controlling the reduction in compressive strength, modulus of elasticity and flexural strength.

- A new prediction model to estimate the modulus of elasticity of rubberized concrete using its compressive strength was proposed.
- A new prediction model to estimate splitting tensile strength of rubberized concrete using its compressive strength was proposed.
- Treatment of the rubber surface with various techniques and the more effective technique were suggested.

5.2 Research Limitations and Recommendations for Future Studies

- Due to the lack of information in the literature only compressive strength, flexural strength and modulus of elasticity are estimated. Hence, expanding the information exciting in the literature through experimental work to estimate more mechanical properties such as dynamic modulus of elasticity and durability properties is recommended.
- This study focused only on untreated rubber, where the constructed model cannot represent the treated ones due to scarce of experimental work in the literature
- This study could not reach to an optimum aggregate replacement by rubber due to the various techniques in testing and testing conditions, which were followed by the researchers.
- This study focused on the engineering properties of rubberized concrete casted in the lab under controlled conditions where the constructed models may not represent casted rubberized concrete on site.

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