Evaluation of mechanical behaviour of the rubberized PCC mortar in fixed W/C ratio

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Abstract: Addition of the waste tire rubber powder to the cement-based products is a solution for the waste problems and protecting environment. Cement-sand mortar is an integral part of masonry buildings and has an important effect on the integrity of the masonry walls. In the current research, mechanical properties and microstructures of the rubberized mortar have been investigated over various lifetimes and the cement content of the mortar was optimized by Pareto solutions. Portland composite cement (PCC) was used for making the rubberized mortar. The amount of rubber additive to the mortar specimens is considered to be 5%. The cement and water content were the variable parameters in the mixture designs while the ratio of W/C was fixed and equalled to 0.6. The microstructure analysis of the test specimens showed that the adherence of the rubber powder particles in the mortar mixture would be more effective with increasing of the cement content, and the negative effects of using rubber powder on the mortar structure can be minimized by choosing the appropriate mixture design. Also, it shows that by increasing the amount of cement in the mixture design of rubberized mortar, the compressive,

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PUBLIC INTEREST STATEMENT
Durability is an important feature in sustainable development. In the building industry, cement sand mortar suffers from shrinkage cracks. It is well obtained from the test results that the addition of rubber particles improves some mechanical properties such as energy absorption and decreases deformation and cracking probability of the mortar. This solution benefits green management in two ways. On the one hand, it leads to the durability of the mortar, and on the other hand, it is used old tires that are harmful to the environment. In this study, a suitable mixing design was obtained in the laboratory by considering the compressive, flexural and tensile behaviour of the mortar. In addition, microstructure of the rubberized mortar has been investigated in this study.
tensile and flexural strengths of the mortar would be very close to the plain mortar specimens, and in some cases, the tensile and flexural strength of the mortar specimens would be increased regarding the plain mortar specimens.

Subjects: Civil, Environmental and Geotechnical Engineering; Concrete & Cement; Waste & Recycling

Key words: Rubberized mortar; cement mortar; Portland Composite Cement (PCC); microstructure; mechanical behavior; Pareto solution

1. Introduction

Every year, millions of tires are being thrown away, and it is estimated that approximately one billion tires are being wasted each year, with over 50% being left unused at the dumps. It is predicted that this number will have been reached to 5 billion tires a year by 2030 (Thomas & Gupta, 2016). Burning the tires is the simplest and cheapest way to dispose them, but it causes serious environmental hazards. One solution is using tire rubber powder in concrete as a structural material (Abdulla & Khtab, 2014; Shah et al., 2014). Studies show that there is a promising future for the use of rubber powder as a part of concrete ingredient. Researches have shown that the efficient concrete can be made by adding waste tire powder. Also, it has a high resistance to thaw and frost, sulfate and acid, and it has good resistance to chloride ion attack and penetration (Thomas & Gupta, 2016).

Many researchers have suggested that using rubber improves abrasion resistance of concrete surfaces (Thomas & Gupta, 2016). Also, according to research, rubber concrete is not suitable for high-temperature applications but has been found to be more effective in absorbing sound than plain concrete (Thomas & Gupta, 2016). Damianti et al. (2013) investigated the effect of adding polyester fibre to cement, sand mortar and found that the tensile strength of the mortar with the aforementioned admixture was more than 30% after 7 days and more than 70% after 28 days (Badagha & Modhera, 2013). Wang et al. (2013) found that the ultrasonic pulse velocity decreased with addition of the rubber powder to dense concrete and the electrical resistance increased with addition of the powder. In addition, there was a favourable linear relationship between ultrasonic pulse speed and electrical resistance with compressive strength. Adding 5% rubber powder significantly increased the corrosion resistance against sulfate, so that the use of waste tire rubber powder can increase the durability of self-compaction concrete (Yung et al., 2013). A study by Christopher et al., has shown that by adding rubber materials to the mortar and applying artificial lightweight aggregates, although the compressive strength decreased, the tensile strength increased (Swan & Bonora, 2017). Also, it was shown that in the experimental research by A. Yilmaz and N. Degirmenci that the specimens with waste tire rubber have higher flexural strength values than the control specimens, due to the effect of rubber fibres (Yilmaz & Degirmenci, 2009). An experimental study by Valeria et al., showed that addition of rubber particles simultaneously reduced the specific gravity of concrete and thermal conductivity (Corinaldesi et al., 2011). In particular, adding 30% to the amount of polyurethane (PU) particles in concrete volume reduced the material weight and thermal conductivity of the composite by 20%, while its compressive strength still remained at more than 15 MPa (threshold value for structural concrete) (Corinaldesi et al., 2011).

Modified rubberized concrete can be used for special applications where the mechanical properties are not the primary requirement, including in the manufacture of sound barriers and cement blocks, as lightweight concrete walls, as well as in structures exposed to aggressive environments. The results of the studies by Oikonomou and Mavridou in 2009 showed a decrease in the mechanical properties of rubber concrete, while an increase in resistance against chloride ion was observed in concrete (Oikonomou & Mavridou, 2009). This suggests that modified mortar and concrete products, using rubber particles as a partial replacement for sand, could be used in applications...
where high resistance against chloride ion penetration is an important parameter. In addition, although the reduction of resistive parameters are definitely a negative property that may prevent the use of tire rubber in cement-based products, it does have positive effects on some other properties. For instance, measurement of absorption of water by immersion under vacuum, showed that the addition of rubber particles decreases absorption of water by immersion under vacuum of the concrete matrix (Oikonomou & Mavridou, 2009). In addition, it causes the potential of corrosion in embedded reinforcement decreased, which is of great practical importance (Aiello & Leuzzi, 2010). M. Aiello and F. Leuzzi showed that the post-cracking behaviour of rubberized concrete was positively affected by the substitution of coarse aggregate with rubber shreds, representing a good energy absorption and ductility indexes for fibrous concrete (Aiello & Leuzzi, 2010).

Rubberized concrete can be used to produce thermal insulation materials for buildings (Guo et al., 2019). The SEM analysis revealed that rubberized concrete specimens contained many voids, and rubber, as a hydrophobic material, weakened the bond between rubber particles and other aggregates, which can explain the reduction of compressive strength of rubber-modified specimens. Under SEM, only a few tiny cracks were found in the rubber-modified samples (Guo et al., 2019). Based on the damping behaviour, mortar containing RTC is recommended for improving performance of masonry wall against earthquake shake (Faizah et al., 2019). The hydrophobic nature of rubber fibres enhances the durability resistance of concrete against acid attack. The rubber fibres acted as a stable barrier that delayed the acid ingress in concrete (Gupta et al., 2019). The incorporation of 5% rubber ash in concrete creates a near similar CSH structure as that of plain concrete (Gupta et al., 2018).

So it is tried in the present study to evaluate the use of rubber powder in cement mortar using a well-developed laboratory program. The ratio of W/C used in the mixture designs represented in this study has a higher value compared to other research programs. Also, due to environmental reasons, Portland Composite Cement (PCC) has been used instead of ordinary Portland cement (OPC). Considering the tensile behaviour of the mortar made using rubber powder and its microstructure are also other prominent features of this research.

2. Experimental program
In this laboratory study, US ASTM standards (C348, C190) as well as European standards EN197-1: 2000 and CECC 260–01 were used for evaluating the rubberized mortar. The main purpose of this study was to investigate the effect of using rubber powder on the properties of commonly used cement sand mortar. Therefore, the selected mixture designs were repeated by adding rubber powder at 5% of sand weight. In this study, different mixture designs were prepared with different cement content (Table 1). The W/C ratio in all of the experimental specimens were 0.6. As it is seen in Table 1, the mixture designs of A to G, are the control mixture designs and the AP to GP are the target mixture. Although the ratio of W/C is constant in all of the mixture designs, the ratio of sand to cement (S/C) has decreased.

Mechanical properties of different mixture designs of the cement mortars represented in this study (Table 1) were investigated with consideration of tensile, compressive and flexural behaviour of tested specimens at different lifetimes. Curing of all experimental specimens were performed at the temperature ranged from 20 to 27.5 °C. Specimens that were processed outside the above temperature were also removed from the test process.

3. Materials properties

3.1. Cement
The Portland Composite Cement (PCC) produced in Bajnord Cement Company was used for construction of the rubberized mortar in this study. The cement ingredients are physically close to the Portland cement 325-1 and chemically similar to the Portland Pozzolana Cement (PPC). Studies show that although its initial strength is somewhat lower than that of ordinary Portland cement, the 90-day
The ingredients of the cement contain 80% clinker and 20% minerals, and it would be beneficial for the environment due to less consumption of the clinker and economic view. The portland cement has a high softness, so it absorbs more hydration water and causes the curing and hydration of the mortar specimens made by PCC is more important than those made with conventional cement and requires a longer retention period of time. Also, using Portland Composite Cement in the mortar causes to produce less heat due to hydration, so it prevents surface of the mortar from cracking.

### 3.2. Tyre rubber powder

In this study, the rubber powder at 5% weight of the sand is intended for use in cement mortar mixture designs. The past results showed that, the compressive strength decreased with increasing percentage of replacement of rubber in concrete, but the lowest decrease in compressive strength of concrete was related to the replacement of 5% cement by rubber.

In this study, the sizes of the rubber powder grains are also smaller than 0.8 mm in accordance with the sand grains (Figure 1).

![Figure 1. Mixture of cement, rubber powder and sand before mixture with water.](image-url)
4. Test results

4.1. Mortar density
Fourteen different mixture designs of powdered and non-powdered specimens were analyzed in this study and 12 specimens were made for each mixture design. The normal weight of mortar in the base mixture design was lower than the normal weight of concrete due to lack of coarse aggregate and weighs approximately 2.3 gf/cm². Whereas, the average normal weight of mortar containing 5% of added rubber powder was 2.0 gf/cm², indicating a decrease of about 15%. The normal weight of uncompressed rubber powder used in this study was about 0.4 gf/cm², so the rubber powder occupies about 4 times of the sand space, and it causes to reduce significantly normal weight of the mortar.

4.2. Mechanical properties

4.2.1. Compressive strength
Figure 2(a,b) shows the 5 × 5 × 5 cm mortar cube moulds and compression test used in this study. Figure 2(c), shows the collapsed specimens by compression load.

Figure 3 shows the diagrams of 7 and 28 days of compressive strength for different mixture designs. Analyzing of the diagrams shows that the varieties of compressive strength of plain mortar and rubberized mortar are different. The compressive strength of plain mortars has slightly decreased with the increase of mortar workability (from A to G), but it seems that increasing the cement content in rubberized mortar has increased the compressive strength of the specimens. As it is seen in Figure 3, the compressive strength of the rubberized mortar specimens with mixture design of AP, BP and CP are significantly lower than the control specimens with mixture design of A, B and C. and addition of the rubber powder to the mixture design greatly reduces the compressive strength of the mortar (more than 20%). However, in other mixture design of rubberized mortar, the compressive strength of the specimens grow up with increasing cement content in subsequent mixture designs and are close to that of the basic specimens. Adding rubber powder to the DP mixture design made the 28-day mortar resistance not significantly changed. However, in
the FP mixture design, compressive strength of rubberized mortar increases 10%. Also, the EP and GP mixture design specimens show a 12% and 17% decrease in compressive strength with comparison to the E and G mixture design specimens, respectively (Table 2). Comparing the 7-day to 28-day compressive strength chart in all of the specimens shows that specimens with rubber powder have achieved a greater portion of their resistance in their 7-day life. The average value of the increase in the compressive, tensile and flexural strengths of the rubberized mortar specimens made is 7%, 8% and 13%, respectively (Table 3). Therefore, it can be concluded that the maintenance and curing of the rubberized mortar are very important during the first week of the construction.

4.2.2. Tensile strength

As shown in Figure 4, briquette tensile specimens were used to perform the tensile tests on the mortar specimens. The tensile loading in the test grows up gradually until the specimen breaks due to tensile failure (Figure 4). Equation 1 is used to determine the tensile stress with respect to the dimensions of the briquette specimen.

$$\sigma_t = \frac{F}{A} = \frac{F}{bt} = 0.16F$$  \hspace{1cm} (1)

In which $\sigma_t$ is the tensile stress and $F$ is the ultimate force of the specimen, and $A$; the specimen cross-sectional area and also $b$; the minimum width of the briquette specimens and $t$; the specimen thicknesses, and both of them are 2.5 cm.

The tensile strength diagrams of 7 and 28-day briquette specimens for different mixture designs are shown in Figure 5. Comparing the tensile strength of rubberized mortar specimens with plain mortars specimens shows differences in their behaviour. Similar to compressive strength tests, the tensile strength of plain mortars have significantly decreased with the increase of mortar workability (from A to G), but the variation trend in rubberized mortar looks similar to compressive strength tests; Increasing the amount of cement paste was more decisive and largely prevented the reduction of tensile strength of the specimens. As it was seen in the specimens

### Table 2. The 28-days strength ratio of rubberized mortar to non-rubberized mortar specimens

| The mixture designs | AP/A | BP/B | CP/C | DP/D | EP/E | FP/F | GP/G |
|---------------------|------|------|------|------|------|------|------|
| Compressive strength | 0.36 | 0.53 | 0.78 | 1.01 | 0.88 | 1.09 | 0.73 |
| Tensile strength     | 0.70 | 0.77 | 0.94 | 1.09 | 0.99 | 1.14 | 0.84 |
| Flexural strength    | 0.63 | 0.71 | 0.80 | 1.06 | 0.92 | 1.19 | 0.93 |

### Table 3. The 28-days strength ratio of tested mortar specimens per 7-days strength

| The mixture designs | A | AP | B | BP | C | CP | D | DP | E | EP | F | FP | G | GP |
|---------------------|---|----|---|----|---|----|---|----|---|----|---|----|---|----|
| Compressive strength ratio | 0.68 | 0.75 | 0.81 | 0.88 | 0.85 | 0.85 | 0.75 | 0.85 | 0.69 | 0.79 | 0.73 | 0.65 | 0.64 | 0.76 |
| Tensile strength ratio    | 0.90 | 0.76 | 0.83 | 0.80 | 0.82 | 0.83 | 0.84 | 0.94 | 0.81 | 0.81 | 0.68 | 0.90 | 0.55 | 0.78 |
| Flexural strength ratio   | 0.78 | 0.70 | 0.72 | 0.84 | 0.79 | 0.84 | 0.69 | 0.79 | 0.75 | 0.81 | 0.61 | 0.88 | 0.66 | 0.84 |
made with mixture designs of A and B, the addition of rubber powder caused to reduce the tensile strength of the specimens significantly compared to the plain mortar specimens. However, with increasing cement content in subsequent mixture designs and with the addition of rubber powder, the tensile strength of the specimens is very close to the strength of the control specimens. Also, in some cases a slight increase was seen in the tensile strength of the specimens. Another point to be drawn from comparing the 7-day to 28-day tensile strength is that the specimens with rubber powder have achieved a greater portion of their resistance in their 7-day life. According to Table 2, by comparing the tensile and compressive strength between rubberized and plain mortar specimen realized that adding rubber powder to the mortar specimens caused to decrease tensile strength less than compressive strength. Even in mixture design of DP and FP, the tensile strength of the rubberized mortar specimens increased in comparison with plain mortar specimens.

4.2.3. Flexural strength
As shown in Figure 4, 4 × 4 × 16 cm specimens were used for flexural tests. The flexural test machine has two supports at 10 cm apart each other and the loading point is exactly at the middle of the two supports. The loading starts by adjustable speed and continues until the flexural failure of the specimen (Figure 6). Equation 2 is also used to calculate the flexural stress according to the specimen dimensions and other specifications.

$$\sigma_{max} = \frac{12PLd}{8d^2} = \frac{3PL}{2d^2} = 0.234375P$$  \hspace{1cm} (2)

In which P; is the value of the point load and L; the distance of the two supports and d; is the height of the section specimen.
Failure of the plain mortar specimens due to flexural test were happening instantly, but there is a kind of plasticity in failure of the rubberized mortar specimens and did not occur unexpectedly. The flexural strength diagrams of 7- and 28-day test specimens for different mixture designs are shown in Figure 7.

The flexural strength of plain mortars has decreased approximately with the increase of mortar workability (from A to G), but the variation trend in rubberized mortar looks similar to compressive and tensile strength tests; Increasing the amount of cement paste was more decisive and largely prevented the reduction of flexural strength of the specimens. As it was seen in the specimens made with mixture designs of A and B, the addition of rubber powder caused to reduce the flexural strength of the specimens significantly compared to the plain mortar specimens. However, with increasing cement content in subsequent mixture designs and with the addition of rubber powder, the flexural strength of the specimens is very close to the strength of the control specimens. Also, in some cases such as mixture design of DP and FP, flexural strength of the specimens increases 6% and 19%, respectively.

4.2.4. Stress–strain curves of the plain and rubberized mortar
The stress–strain behaviour curve of the plain and rubberized mortar specimens for tensile and compressive behaviour is shown in Figure 8(a,b), respectively.

As noted earlier and according to Figure 8(a), the maximum tensile stresses of plain and rubberized mortar specimens for mixture design of A and AP were 31.10 and 23.14 kg/cm², respectively. It shows
a decrease of 25% in mortar specimens made by using rubber powder. Also, the maximum compressive stresses of plain and rubberized mortar specimens for mixture design of C and CP were 235.96 and 207.92 kg/cm², respectively, which is a decrease of 12% in the mortar specimens made by using rubber powder. The ratio of maximum compressive strength to tensile strength in plain and rubberized mortars is 7.5 and 8.9 times, respectively. As shown in Figure 8(a,b), the maximum compressive and tensile strain did not reduce in rubberized mortar. So, modulus of elasticity in rubberized mortar has been decreased and the mortar showed softer behaviour. The ratio of the maximum tensile to compressive strain is also about 10 in plain and rubberized mortars.

4.3. Microstructure of the rubberized mortar

Microstructures of the mortar specimens and status of the rubber powder in the mortar were investigated by Scanning electron microscope in this study. In the scanning electron microscope, an electron beam is radiated to the specimen. Then, two or three focusing lenses minimize the electron beam down to a diameter of 2 to 10 nm when dealing with the specimen. The electrons are usually accelerated between 1 and 30 kV, and in this study the acceleration is set to 20 kV.

Figure 9 shows a mortar specimen made of rubber powder characterized by Scanning Electron Microscope (SEM) and marking system with elemental analysis technology at the specified point (Spectrum 1). As shown in Table 4, more than 96% atomic and 90% weight of the specified point is identified as a carbon element, indicating the material of the rubber powder.

Figure 10 also shows a specimen of a composite portland cement mortar and aggregate adjacent to an air bubble characterized by Scanning Electron Microscope (SEM) system with spectrum element analysis technology (Spectrum 2). The elements and their constituents have been identified in Table 5. The specified elements are all components of the composite Portland cement matrix. More than half of this mixture is made up of oxygen combined with the main cement element. After that, the highest content of the cement matrix was related to calcium with 20% weight and silicon with 8.7%. The percentages of aluminum, magnesium and iron are also negligible. The identified elements and compounds comply with the standards of cement

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**Table 4. The comprising elements of the marked spot in microscopic image**

| Element | Weight% | Atomic% |
|---------|---------|---------|
| C       | 90.56   | 96.89   |
| Si      | 1.63    | 0.74    |
| S       | 3.70    | 1.48    |
| Ca      | 0.59    | 0.19    |
| Zn      | 3.53    | 0.69    |
| Totals  | 100.00  | 100.00  |
In addition, the aggregates used in the experimental specimens are also calcium aggregates.

In Figure 11(a), the status of the cement paste and aggregates as well as the cracks formed in the aggregates are shown in the plain mortar specimen. The crack on the aggregate in this specimen indicates the correct failure of the specimen. Also the cohesion of the mortar ingredients is evident in this figure. Figure 11(b) shows the arrangement of the rubber powder particles in the cement paste of mixture design B. According to the figure, there are some significant cracks and air bubbles inside the rubberized mortar and constituents of the rubberized mortar specimen have fewer adherences than the plain mortar specimen. As it was mentioned, the rubberized mortar specimen made with mixture design B, has less compressive and flexural and tensile strengths than the plain mortar specimens.

The way the rubber powder is placed in the cement paste shows that the consistency of the rubber powder in this sample is not similar to the usual connections between the cement paste and the aggregates, and cracks and cavities and discontinuities can be seen in it. Inside the rubber powder, there are also significant cracks and crevices. In addition, the presence of small air

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**Table 5. The comprising elements of the marked spot in microscopic image**

| Element | Weight% | Atomic% | Analysed |
|---------|---------|---------|----------|
| C       | 11.36   | 17.44   | CaCO₃    |
| Mg      | 1.54    | 1.17    | MgO      |
| Al      | 1.70    | 1.16    | Al₂O₃    |
| Si      | 8.72    | 5.72    | SiO₂     |
| Ca      | 20.07   | 9.24    | CaCO₃    |
| O       | 56.62   | 65.27   |          |
| Totals  | 100.00  | 100.00  |          |

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Figure 10. The Microscopic image of the mortar specimen made of composite Portland cement.

Figure 11. (a) Microscopic image of the simple mortar specimen by 250x magnification (mixture design B). (b) Microscopic image of the rubberized mortar specimen by 350x magnification (mixture design BP).
bubbles that are not visible to the naked eye can be seen around the rubber powder, which indicates the conditions for the beginning of cracks around the rubber powder. Comparing this photo with the powerless sample, the reduction of compressive, flexural and tensile strength can be justified.

Figure 12 shows a microscopic image of the rubberized mortar specimen made by mixture design F with a magnification of 1000 times. According to Figure 12, the particle width of the rubber powder in this image is about 50 nm. As it was mentioned in the previous section, no significant decrease was observed in the strength of the rubberized mortar made by mixture designs of D, E and F (Figures 3, 5 and 7). In this case, constituents of the rubberized mortar specimen have more adherence than the other rubberized mortar specimen due to more cement content in the mixture design. Due to more fluency of the cement paste in the mortar specimen, it had better Continuity and adhesion to the cement matrix. The rubber powder in this sample is completely covered by cement paste.

It is also clear from comparing Figure 12 with Figure 11(b) that air bubbles around the rubber powder and the resulting cracks are reduced by increasing the volume of cement paste in comparison with aggregates (while the ratio of water to cement is constant), and so it leads to tensile strength of the mortar specimens do not decrease

5. Optimizing the cement content
In this section, amount of cement for 7-day and 28-day strengths of the experimental mortar specimens has been optimized. To optimize this parameter, at first a polynomial function has been fitted for each strength of the mortar specimens including compressive, tensile and flexural strength. Various measures are employed to check how well the fitness function models the data. These measures are P-value, R-square (R2) and adjusted R-square (aR2). P-value is the significance of the model as a probability. This compares the variance attributed to the model with the variance of the residual. R-square is 1 minus the ratio of sum of the squares of the residuals divided by the sum of the squares of the differences between response fitness value and the mean of response value. This will equal 1 for a perfect and tend towards 0 for a bad fit. In other words, R-square is the ratio of variation that is explained by the curve-fitting model to the total variation in the model. In most situations, irreducible errors in measurement will prevent the model from explaining all the variation. Models using a larger set of factors may produce an R-square value that is closer to 1. However, it may be that the additional factors are essentially modelling noise. Adjusted R-square is R-square adjusted downward to compensate for over fitting. The larger the number of independent variables, the lower the adjusted R-square value will be. When using fitness function models with a larger number of independent variables, the additional variables may be simply modeling noise.
Figure 12. Fitted curve for 7-day strengths of the experimental mortar specimens (all strengths are in kg/cm²). Fitted curve for 28-day strengths of the experimental mortar specimens (all of strengths are in kg/cm²).

For these data, polynomial fitness function has been provided. 2nd order (quadratic regression), 3rd order (cubic regression), 4th order (quartic regression) and 5th order (quantic regression) have been fitted for data. Results have been shown in Tables 6 and 7 for 7-day and 28-day strengths of the experimental mortar specimens, respectively.

In Tables 6 and 7, first the P-value should be checked. Due to confidence level of %95, when P-value is less than 0.05, it means that there is a probability of at least %95 that the result is reliable. Among all remind regression models, less P-value is selected due to its reliability. Also, the larger R-square represents the better fit of the regression model. Moreover, the larger adjusted R-square value shows the better fitness model. In 7-day tensile strength, confidence level of 90% is selected. In this case, the reliability of fitness function is less than other cases. Moreover, the R-square and adjusted R-square in this case did not represent a good model. In Figures 12 and 13, the fitted curves have been demonstrated for 7-day and 28-day, respectively.

According to the obtained function, for each of them the optimum value of cement has been described in Table 8.

As it can be seen in Table 8, the cement optimum value is different for each strength. Therefore, because of three separate strengths, there is no specific cement optimum value. As a result, we need a
Table 6. Goodness measures results for 7-day strengths of the experimental mortar specimens

|                | Model                      | R2     | aR2    | P       |
|----------------|----------------------------|--------|--------|---------|
| **Compressive**| **strength**               |        |        |         |
| Quadratic regression | $y = -2677.146 + 1.65585x - 0.0002385x^2$ | 0.9079 | 0.8618 | 0.008489 |
| Cubic regression | $y = -11555.37 + 9.619211x - 0.002599729x^2 + 2.314931e-7x^3$ | 0.9831 | 0.9661 | 0.003721 |
| Quartic regression | $y = 34936.6 - 6.4600691x + 0.02221669x^2 - 0.00000466148x^3 + 3.597775e-10x^4$ | 0.9893 | 0.9949 | 0.003415 |
| Quantic regression | $y = 133524.2 - 193.3915x + 0.1098942x^2 - 0.0003068641x^3 + 4.202486e-9x^4 - 2.260417e-13x^5$ | 0.9987 | 0.9919 | 0.06221  |
| **Tensile**     | **strength**               |        |        |         |
| Quadratic regression | $y = -209.7593 + 0.1388333x - 0.0002032738x^2$ | 0.6995 | 0.5493 | 0.09028  |
| Cubic regression | $y = -366.896 + 0.2797778x - 0.0006211905x^2 + 4.097222e-9x^3$ | 0.7024 | 0.4049 | 0.2495   |
| Quartic regression | $y = -8792.169 + 10.36034x - 0.00455935x^2 + 8.908018e-7x^3 - 6.519886e-11x^4$ | 0.764  | 0.292  | 0.4163   |
| Quantic regression | $y = 144314 - 218.5272x + 0.1317431x^2 - 0.000395258x^3 + 5.902509e-9x^4 - 3.510417e-13x^5$ | 0.8722 | 0.2332 | 0.5689   |
| **Flexural**    | **strength**               |        |        |         |
| Quadratic regression | $y = -342.4107 + 0.2225131x - 0.000308333x^2$ | 0.8365 | 0.7547 | 0.02675  |
| Cubic regression | $y = -1622.142 + 1.370374x - 0.003711875x^2 + 3.336806e-8x^3$ | 0.8776 | 0.7553 | 0.06993  |
| Quartic regression | $y = 26399.3 + 31.01543x - 0.01359671x^2 + 0.000002641001x^3 - 1.917377e-10x^4$ | 0.9916 | 0.9748 | 0.01671  |
| Quantic regression | $y = -38552.38 + 49.18381x - 0.02441597x^2 + 0.000005849143x^3 - 6.654356e-10x^4 + 2.786458e-14x^5$ | 0.9918 | 0.9505 | 0.1535   |

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| Goodness measures results for 28-day strengths of the experimental mortar specimens |
|---------------------------------------------|-----------------|-----------------|-----------------|
| **Model** | **R^2** | **aR^2** | **P** |
| **Compressive strength** | | | |
| Quadratic regression | \( y = -2832.234 + 1.737107x - 0.0002452321x^2 \) | 0.9653 | 0.9479 | 0.001205 |
| Cubic regression | \( y = -4.25179 + 3.010385x - 0.006227738x^2 + 3.701389e-8x^3 \) | 0.9666 | 0.9333 | 0.01024 |
| Quartic regression | \( y = -2.301745 + 25.46288x - 0.01063948x^2 + 0.0000020111970x^3 - 1.452178e-10x^4 \) | 0.9684 | 0.9052 | 0.06221 |
| Quantic regression | \( y = 1006815 - 1514.095x + 0.9061664x^2 - 0.0002698406x^3 + 3.999515e-8x^4 - 2.361198e-12x^5 \) | 0.9964 | 0.9784 | 0.1018 |
| **Tensile strength** | | | |
| Quadratic regression | \( y = -139.1421 + 0.09934345x - 0.00001448512x^2 \) | 0.6807 | 0.521 | 0.102 |
| Cubic regression | \( y = 413.4995 - 0.396351x + 0.000132494x^2 - 1.440972e-8x^3 \) | 0.7481 | 0.4961 | 0.1976 |
| Quartic regression | \( y = -10199.16 + 12.30135x - 0.00532319x^2 + 0.000001102503x^3 - 8.21595e-11x^4 \) | 0.9315 | 0.7944 | 0.1323 |
| Quantic regression | \( y = 76896.35 - 118.557x + 0.0726892x^2 - 0.00002698406x^3 + 3.355504e-9x^4 - 2.361198e-12x^5 \) | 0.9989 | 0.9933 | 0.04687 |
| **Flexural strength** | | | |
| Quadratic regression | \( y = -323.3429 + 0.220999x - 0.00003101274x^2 \) | 0.9438 | 0.9158 | 0.003153 |
| Cubic regression | \( y = -895.9595 + 0.7346105x - 0.0001833244x^2 + 1.440972e-8x^3 \) | 0.9559 | 0.9118 | 0.0155 |
| Quartic regression | \( y = -6317.014 + 7.220725x - 0.0030798698x^2 + 5.854609e-7x^3 - 1.95076e-11x^4 \) | 0.9639 | 0.8917 | 0.07088 |
| Quantic regression | \( y = -126655.3 + 187.1216x - 0.1102079x^2 + 0.00003235207x^3 - 4.732446e-9x^4 + 2.759115e-13x^5 \) | 0.9849 | 0.9091 | 0.2074 |
Pareto optimal or Pareto solutions. Pareto solutions are defined when none of strength functions can be improved in value without considering some of the other strength values. According to this definition, we use linear scalarization method to find the Pareto solutions for 7-day and 28-day experiments. In this method, a single strength optimization problem has been formulated such that optimal solutions of this function are the Pareto optimal solutions of the problem. We use $\max(w_1 \times CS + w_2 \times TS + w_3 \times FS)$ to find the Pareto solutions, where the weights of the compressive strength (CS), tensile strength (TS) and flexural strength (FS) are $w_1$, $w_2$ and $w_3$, respectively. Moreover, these parameters are the parameters of the scalarization. According to this function, the obtained Pareto solutions for 7-day and 28-day experiments have been shown in Figures 13 and 14, respectively. It should be noted that the range of cement value in the Pareto solutions for 7-day and 28-day experiments are [3360.508gr, 3812.077gr] and [3542.162gr, 3646.707gr], respectively. Each decision maker according to his/her weight of strength can select one of these Pareto solutions as the final cement value.

6. Conclusion
One of the important differences between concrete and mortar is that the mortar mixture has not any coarse aggregate and is more fluent. This difference leads to increase of cement paste in the
Figure 14. Pareto solutions for 28-day experiments from 6 views (all strengths are in kg/cm²).

mortar specimens. Therefore, the behaviour of mortar containing rubber powder is somewhat different from rubber powder concrete and requires separate and more studies. In this experimental study, the effect of addition of rubber powder to the mortar mixture made of composite Portland cement was investigated. More than 500 mortar specimens have been fabricated in various mixture designs and tensile, compressive and flexural tests have been carried out over various lifetimes. In addition, the microstructure of the rubberized mortar specimens has been investigated and compared with the plain mortar specimens. Finally, Pareto solutions were used for optimization of the mechanical strengths of the experimental mortar specimens. The variable parameters in the mixture design are the cement content and workability of the mortar specimens, while the ratio of W/C in the mortar specimens is set to 0.6. Addition of the rubber powder to the mortar specimens is also considered to be 5%. The results of the represented study are as follows:

- The microstructure analysis of the specimens shows that with increasing of the cement content in the mortar, the adherence of the rubber powder particles in the mortar mixture would be more effective and have stronger bonding. In other words, with the increase in the cement content at a constant ratio of W/C (0.6) and an overall increase in volume of the water and the cement regarding to the volume of the aggregate, rubberized mortar showed stronger behaviour.
- By increasing the amount of cement in the mixture design of rubberized mortar, the compressive, tensile and flexural strengths of the mortar would be very close to the plain mortar specimens, and in some cases, the tensile and flexural strength of the mortar specimens would be increased.
- Adding 5% rubber powder in mixture design with sand to cement ratio between 2.5 and 3 (DP, EP and FP mixture designs) did not show a significant decrease in the compressive strength of the mortar. Also in these mixture designs, tensile and flexural strength of the mortar specimens increased regarding to the plain mortar specimens. Among all of tested mixture designs, the mixture design of DP would be recommended due to the low consumption of the cement.
by increasing the volume of cement paste in comparison with aggregates (while the ratio of water to cement is constant) air bubbles around the rubber powder and the resulting cracks are reduced, and so it leads to tensile strength of the mortar specimens do not decrease.

- Optimizing the mechanical strengths of the mortar specimens by Pareto solution showed that the optimized range of cement for 7-day and 28-day experiments are set at [3360.508gr, 3812.077gr] and [3542.162gr, 3646.707gr], respectively.

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