Utilizing a Different Technique for Improving Micro and Macro Characteristics of Coarse Recycled Concrete Aggregate

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Abstract:

Sustainable development has significance for obvious and relevant reasons in all areas of civil transportation infrastructure. In the asphalt highway industry, a large number of innovative materials and technologies are explored in order to evaluate their suitability in the design, construction and maintenance of pavements. The utilization of Recycled Concrete Aggregate (RCA) is becoming a highly interesting issue in Canada, and worldwide, due to many reasons including lowering consumption of virgin materials, decreasing waste materials in landfills and reducing environmental problems. The main objective of this research is to investigate the utilization of different technique which includes the combination of various treatment methods for enhancing micro and macro characteristics of coarse recycled concrete aggregate (CRCA). Macro properties of CRCA included specific gravity, water absorption, abrasion loss and adhered mortar loss, whereas micro characteristics involved porosity and atomic Ca/Si ratio. In addition, the influence of each treatment type on the micro and macro properties of CRCA was examined separately. Furthermore, the relations among different micro and macro characteristics impacted by various treatment methods are explored. In order to achieve the objective, pre-soaking and heat treatment followed by different types of short mechanical treatment are conducted to evaluate macro and micro properties of CRCA before and after a combination of various treatment types. Heat treatments included various temperatures (250ºC, 350ºC and 500ºC). Presoaking method involved the use of strong acid, HCl, and weak acid $C_2H_4O_2$, whereas short mechanical treatment included the utilization of a Micro-Deval device with two different testing techniques with/without steel balls. The obtained results revealed that the utilization of a combination of methods between different treatment types is a highly successful technique for improving macro and micro characteristics of CRCA compared with separate treatments. The combination between acetic acid treatment and short mechanical method with steel ball exhibits the best performance by reducing the water absorption by 36.9%. The use of weak acid is more effective than strong acid in enhancing macro and micro properties in terms of abrasion loss, adhered mortar loss and atomic Ca/Si ratio, whereas acid treatment with strong acid appears to be more efficient in improving water absorption and porosity. Heat treatment type at temperatures between 350°C-500°C has a noticeable negative impacts on different macro and micro CRCA characteristics. Different macro characteristics of CRCA including water absorption and abrasion loss and adhered mortar loss are strongly correlated with various micro properties in terms of porosity and atomic Ca/Si ratio.

Keywords: Coarse recycled concrete aggregate (CRCA), Micro properties, Macro properties, Heat treatment, Acid treatment, Combination, Short mechanical treatment with/without ball.

1. Introduction

Consciousness of the need for sustainable development and preservation of non-renewable aggregate resources has been rising largely in Ontario, throughout Canada and all over the world over the past 15 years. The increased cost of energy with this consciousness has contributed to make a changes in the recycling and reuse ‘landfill’ resulting to considerable increase amounts of these materials which are finished into using in the transportation section (MONRO, 2009). Researchers of transportation believe that Warm Mix Asphalt (WMA) and recycling of waste materials are examples of materials that will achieve the future sustainability in the asphalt highway industry (Mills-Beale & You, 2010). Sustainability is defined according to the World Commission on Environment and Development as “Meeting the needs of the present without compromising the ability of the future generations to meet their own needs” (Naik & Moriconi, 2005). The requirements of sustainable concrete construction development aim to achieve two main goals: reasonable use of natural materials and lowering environmental influence. The first goal is achieved by using waste materials and decreasing extraction of natural aggregate, while the second is accomplished through decreasing carbon emissions (Naik & Moriconi, 2005).

Billions of tons of concrete were extensively consumed in to construction of buildings, bridges, dams, roads, and other structures since World War II. The construction materials for these structures are disposed as a waste material into landfills after their service life is completed (Cosper, 2004). Construction materials can be classified into two main groups: waste and recycled materials. Recycled materials are originally formed from waste materials after some processes, while waste materials can be divided into four main types: Industrial wastes; Municipal/domestic wastes; Mining wastes and Construction and demolition (C&D) wastes such as RCA (Ahmedzade & Sengoz, 2009; Ektas & Karacasu, 2012). Recycled concrete aggregates which, is produced directly from the crushing process for the local construction and demolition waste materials to smaller particles, playing an important role not only by reducing natural resources consumption but also through the improvement of sustainability due to reducing the landfill usage (Cui et al, 2014; Güneyisi et al, 2014).

2. Literature review

Recycled concrete aggregate (RCA) is a composite material, where in natural coarse and fine aggregates (65-70%) are coated by cement mortar (30-35%) (Paranavithana and Mohajerani, 2006; Kong et al., 2010; Ismail and Ramli, 2013). The RCA characteristics are strongly affected by diverse factors: types of crushing method; particle size; strength of the parent concrete; quality and the amount of adhered mortar; tiny cracks and weak adhesion between mortar and aggregate (Tam et al., 2007; Akbarnezhad et al., 2011; Lee et al., 2012; Pérez et al., 2012; Spaeth & Tegguer, 2013; Güneyisi et al., 2014; Purushothaman et al. 2014). The properties of RCA are different to natural aggregate due to the existence of an adhered mortar layer on the surface of the RCA (Behring, 2013). RCA is generally rough, porous, flat and irregular, but in particular, it is characterized by a lower bulk and specific gravity, and a significantly higher water absorption, which results in inferior mechanical properties (Malešev et al., 2010; Lee et al., 2012; Pepe et al., 2014). The higher porosity characterizing the adhered mortar layer is the main reason behind this behavior (Pepe et al., 2014). As it is well known in material and soil science, the porosity is a measure of the voids in a material or the percentage of voids to the total volume of a material. The increase of porosity for a material indicates the existence of a large number of voids and vice versa. These voids work to lower density and absorb large quantities of water. Therefore, density and water absorption are highly dependent on porosity of material as the following simple equations:

$$V = V_s + V_V \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$Bulk\ density = \frac{W_S}{V} \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$Particle\ Density = \frac{W_S}{V_S} \ldots\ldots\ldots\ldots (3)$$

$$Porosity, n = \frac{V_v}{V} \ldots\ldots\ldots\ldots\ldots\ldots.. (4)$$

Where: V = total volume (solid volume & void volume), V_S = solid volume, V_V = void volume, W_S = weight of solid.

As a result, the general major reason for poor quality for RCA appears to be due to the adhered mortar layer, which is more porous and less dense than crushed stone (Tam et al., 2007; Gul, 2008; Lee et al., 2012; Pérez et al., 2012), while the porosity of RCA is the main specific reason. These characteristics have become restrictions for using RCA in some applications.

In 2000, the primary efforts for improving RCA properties were recorded through several investigations (Montgomery, 1998; Tateyashiki et al., 2001; Tamura et al., 2002). The fundamentals of those studies were originally based on techniques: ball milling and heating and rubbing that have become the two main methods for producing RCA from construction and demolished concrete; namely, refining and replacing methods. Figure 1 demonstrates a schematic diagram of various treatment methods for enhancing physical properties of RCA in the literature that are chronologically arranged since 2000 until the present time.

Recently, combination technique between different treatment methods for enhancing physical properties of RCA has become a highly interesting topic. Al-Bayati et al. (2016) have investigated the effect of combination among various treatment methods in a comprehensive study for enhancing the physical and morphological properties of coarse recycled concrete aggregate (CRCA). Various treatment methods including heat treatment at temperatures ranging between 20°C and 750°C, acid treatment through utilizing novel technique which includes the use of weak acid and strong acid, and short mechanical treatment using a Micro-Deval device for 15 min without metal balls in a dry condition. The findings of the study revealed that the combination of heat treatment at 350°C and short mechanical treatment led to the best performance for enhancing physical properties, with more than 27% lowering of water absorption. The use of weak acid treatment is an effective, safe and more preferable than strong acid. Heat treatment appears to have negative effects when used at higher temperatures (500°C and 750°C).

With the increasing use of advanced technological techniques worldwide, the characteristics of materials at micro and macro levels are becoming an attractive topics in many fields of knowledge. More recently, researchers of the construction and highway industry have highlighted particular efforts on the micro and macro properties of concrete to investigate how the addition of various materials influences the ability to enhance characteristics of concrete at micro and macro levels. Kavitha et al. (2015) examined the effects of metakaolin (MK) on macrolevel and microlevel properties of self-compacting concrete (SCC) at various percentages (5, 10 and 15 wt. %) as a replacement for cement. The macrolevel properties included compressive strength and split tensile strength, whereas the microlevel properties involved the width of microcracks and atomic Ca/Si ratio. The obtained results indicated that there is a considerable decrease in microcrack width due to pozzolanic action of MK that reduces the calcium hydroxide (CH) and lowers Ca/Si ratio. Additionally, it was found that the replacement level of 10 wt. % MK, which is optimum replacement, leads to substantial improvement in the compressive strength and split tensile strength (macrolevel properties). The study concluded that the enhancement of microlevel properties resulted in substantial improvement of macrolevel properties.

Ramezanianpour et al. (2015) investigated the influence of different concentrations of natural zeolite (10 and 15% by wt.) as a replacement for Portland cement material at different ages (7, 28, 90, and 270 days) on macro and micro level properties of concrete and paste. Macro level properties included: compressive strength; tensile split strength; water permeability; capillary absorption; chloride penetrability; electrical resistivity and carbonation, whereas micro level properties included microstructure study of the paste and transition zone. The outcomes of the study demonstrated that the addition of natural zeolite led to significant reduction in water permeability and capillary absorption, whereas rapid chloride permeability and electrical resistivity, and increased depth of carbonation are obtained. It was also observed that 10% and 15% of natural zeolite provided similar strength and marginally lower than that of reference concrete respectively. The obtained results concluded that there is a considerable improvement at the microstructural level for the cement paste and transition zone. This enhancement was mainly attributed to significant reduction in porosity and tiny cracks for paste and formation of a secondary C-S-H due to pozzolanic reaction in the transition zone. The influence of class F fly ash on the micro and macrolevel properties of self-compacting concrete (SCC) at different curing times (28, 56 and 112 days) was explored through Jawahar's investigation. A conventional concrete (CC) having an equivalent 28-day SCC compressive strength has also been examined at different ages. Microcrack width between aggregate and adhered mortar, and atomic Calcium: Silicon (Ca/Si) ratio were considered as a micro level properties. Whereas, the macrolevel properties included compressive strength, modulus of elasticity and split tensile strength. The findings of the research demonstrated that there is a considerable effect of curing time on microcrack width of SCC, resulting in significant reduction of microcrack width with increasing curing time. The improvement is mainly attributed to pozzolanic action of F fly ash which improved the microlevel properties of SCC through densifying microstructure and reducing microcracking width and Ca/Si ratio. This can lead to improving the bond between aggregate and paste and enhancing the macrolevel mechanical properties; therefore, it was concluded that microlevel and macrolevel properties were reasonably correlated (Jawahar et al., 2013).

While comprehensively scanning the literature related to methods and techniques of enhancing physical characteristics of RCA, it should be noted that investigations of mirco and macro level properties are primarily limited to various types of concrete, as mentioned above. Until now, none of the literature studies mentioned above have ever explored the effect of various treatments and techniques on enhancing micro and macro characteristics of RCA, resulting in an obvious gap in this area. Therefore, this paper attempts to examine the influence of various treatments at different technique on enhancing micro and macro level properties of coarse recycled concrete aggregate.

3. Research objective

The main objective of this investigation is to examine the influence of a different technique which includes the combination of various treatment methods on improving micro and macro characteristics of coarse recycled concrete aggregate. Additionally, the effect of each treatment type on micro and macro properties of CRCA was explored separately. A complementary objective is to examine the relation among various micro and macro properties of CRCA under impact of diverse treatment types including combination of different treatment methods.

4. Materials and methods

4.1 Materials

The RCA material is classified as a granular A according to the Ontario Provincial Standard Specifications (OPSS.MUNI 1010). The RCA was produced by Steed and Evans Ltd in the Region of Waterloo, Ontario. In this study, the CRCA is defined as the sieve fraction retained between 4.75 and 19 mm. The optical image of RCA is shown in Figure 2. The results of macro and some physical properties of untreated CRCA are shown in Table1.

4.2 Methods

The CRCA was washed thoroughly, so that all noticeable impurities such as wood chips and others were removed. Then, the CRCA was dried in an oven at 105±5°C for 24 hours before conducting different types of treatments and tests. The untreated CRCA tests was performed at room temperature (20°C), whereas the treatments included different types and conditions.

4.2.1 Pre-soaking method

The CRCA was soaked in an acidic solution composed of Hydrochloric acid (HCl) (37%) and Acetic acid ($C2H4O2$) (99.7%) obtained from Sigma-Aldrich at a low concentration of 0.1 M for 24 hours at room temperature around 20°C. Low concentration of acidic solution was chosen to provide a suitable acidic environment for CRCA without an influence on the RCA quality. The CRCA was submerged in distilled water and drained to remove acidic solution, then the samples were dried at 105±5°C for 24 hours to prepare for testing as shown in Fig. 2. The treatment method by using strong HCl is adopted from the literature (Tam et al., 2007; Ismail & Ramli, 2013; Purushothaman et al., 2014).

4.2.2 Heat treatment method

The CRCA samples were heated at three different temperatures: 250°C, 350°C and 500°C for a period of one hour in a conventional electric oven.

4.2.3 Macro level characteristics

Various tests were performed and considered as a macro properties in this investigation including water absorption, specific gravity, abrasion resistance and adhered mortar loss.

4.2.4 Micro level characteristics

Different tests were conducted and considered as a micro characteristics in this research including porosity and atomic Ca/Si ratio. The results of macro characteristics and physical properties of untreated CRCA are shown in Table1.

5. Results and discussion

5.1 Effect of treatment methods on macro properties of CRCA

5.1.1 Water absorption and specific gravity

The effect of different treatment types on water absorption, specific gravity, apparent specific gravity and bulk relative density (SSD) for recycled concrete aggregates is presented in Table 2. Whereas, Figures 3 & 4 reveal water absorption and apparent specific gravity behavior through heat treatment. The obtained results demonstrate that various treatment methods are successful for improving water absorption and specific gravity of CRCA. Treatment types effectively remove a portion of adhered mortar, which is classified a weak material compared with aggregate, under different effects resulting in a significant improvement to water absorption and specific gravity. Comparable findings were recorded by numerous investigations (Shima et al., 2005; Tam et al., 2007; Ismail & Ramli, 2013; Güneyisi et al., 2014). Among different treatment methods, heat treatment type at 350°C has a maximum impact by increasing specific gravity and lowering water absorption with an approximate decrease of 11.2%. Whereas, treatment with HCl appears to be more effective than acetic acid with a decrease 10.4% for water absorption. By contrast, It is observed that there is highly increased to water absorption for heat treatment at 500°C that reached to be more than water absorption of untreated CRCA. Al-Bayati et al. (2016) stated that CRCA exposed to thermal expansion and consequent internal stresses highly affected the mechanical performance of concrete in the temperature range between 400°C and 600°C. Therefore, CRCA suffers widely from degradation, and there is a breakdown and mass loss of concrete particles due to exposure to high temperatures. This explanation was highlighted in a previous studies (Wong et al., 2007; Vieira et al., 2011; Gupta et al., 2012).The degradation and mass loss lead to lowering specific gravity, whereas internal stress due to thermal expansion can cause microcracks and microvoids resulting in higher porosity and water absorption.

The outcomes also indicate that there is a good relationship between water absorption and apparent specific gravity with heat treatment temperatures due to obtaining high regression values relatively. However, heat treatment at high temperatures that are ranged between 350°C and 500°C has a negative influence by lowering apparent specific gravity and increasing water absorption. Moreover, it can be clearly concluded that characteristics have an opposite behavior though two properties exhibit as a polynomial equation.

5.1.2 Abrasion resistance

Figure 5 demonstrates the obtained results after one cycle of abrasion resistance test in the Micro-Deval device, whereas Figure 6 shows abrasion loss behavior through heat treatment. It is generally accepted that the abrasion resistance test for aggregate materials refers to durability characteristics under wet conditions and a minimum percentage of abrasion loss indicates to losing lower amounts of adhered mortar and vice versa. The obtained outcomes clearly reveals that CRCA without treatment has a lower percentage of abrasion loss compared to CRCA with various treatment types. This refers to a positive and successful influence for various treatments on removing adhered mortar from CRCA at different percentages depending on treatment type.

Compared to untreated CRCA, the percentage of loss for CRCA is increased with the increase of heat treatment temperature, by 4.5% and 11% at temperatures 250°C and 350°C respectively. On the other hand, it is obviously to consider that there is considerable difference in the percentage of loss, increasing for CRCA which, when treated with temperature 500°C, reached 64.1%. The dramatic increase of abrasion loss is mainly attributed to broad degradation for CRCA surface. Therefore, the result of the abrasion resistance tests at 500°C emphasizes water absorption behaviour at the same temperature. The aggregate suffered from thermal expansion followed by internal stresses due to exposure to high temperature (Wong et al., 2007; Vieira et al., 2011; Gupta et al., 2012). As a result, breakdown of material and mass loss are predominantly occurred that leads to easy removal of adhered mortar under the influence of steel balls that are existed within a normal requirements of the Micro-Deval test.

The obtained results also demonstrated that abrasion loss is strongly correlated with temperature of heat treatment due to obtaining an optimum regression. Polynomial equation obviously reflects behavior of abrasion loss through this type of treatment. It is interesting to note that soaking in the low concentration of HCl solution increased the percentage of loss by

5.1%, whereas this percentage increased by 9.5% for acetic acid solution indicating CRCA surface is highly affected by weak acid more than strong acid.

5.1.3 Adhered Mortar Loss

The obtained results of adhered mortar loss and its behavior through heat treatment were further analyzed and presented in Figures 7 and 8 respectively. As it is mentioned earlier in abrasion loss section, the amounts of adhered mortar loss thoroughly reflect results of abrasion loss test, which can be defined as resistance to mechanical abrasion, consequently it is highly related with durability characteristics. The obtained consequences reveal that untreated CRCA has a minimum percentage of adhered mortar loss compared to CRCA with diverse treatment types that indicate an effective impact for different treatment methods on removing adhered mortar from CRCA at various percentages. For heat treatment, the adhered mortar loss is increased by 38.9%, 124.1% for CRCA treated with temperature at 250°C and 350°C, respectively. Whereas, adhered mortar loss at 500°C is sharply increased by 365.7% recording an excessive influence for heat treatment type. It is also observed that adhered mortar loss is increased by 141.7% and 115.7% for weak and strong acid, respectively, registering successful treatment for both types of acids. However, weak acid seems to be more effective for removing adhered mortar than strong acid. As a consequence, the obtained results of adhered mortar loss and abrasion loss tests are thoroughly consistent. As can be seen in Figure 8, an exponential equation completely reflects strong relationship between adhered mortar loss and temperature of treatment due to obtaining significant regression.

5.2 Influence of combination between different treatments on macro properties

5.2.1 Water absorption and specific gravity

Table 3 summarizes the obtained results of water absorption and specific gravity for CRCA after the adhered mortar loss test. These results represent two stages of treatment: the first stage included the acid and heat treatment, whereas the adhered mortar test or short mechanical treatment was performed in the second stage, which was conducted using two different techniques with/and without steel balls. Therefore, comparison with the untreated CRCA is an equitable evaluation for diverse conditions and methods.

Generally, compared with untreated CRCA, there is a considerable improvement in both the specific gravity and water absorption. It is interesting to note that the percentage of water absorption reduces from 3.74% to 2.36% due to the combination of acetic acid and short mechanical method with steel ball, which has recorded as the best performance of 36.9% reduction. This was followed by integration of thermal treatment at 350°C and short mechanical treatment with steel ball by 26.7%, then the combination of strong acid and the same mechanical process by 23%, compared to untreated CRCA. Surprisingly enough, the considerable difference of decreasing water absorption was obtained between weak and strong acid treatment through combination with short mechanical treatment with steel ball. This indicates weak acid seems to be more effective and preferable due to different concerns that related with acid attacks to aggregate surfaces.

Experimental results of the water absorption through combination between heat and acid treatment with both types of short mechanical treatment were graphically analyzed in Figures 9 (a & b).As can be seen in Figure 9 (a), the results demonstrate that there is a considerable decrease of water absorption with increasing temperatures that are ranged between (20°C-300°C) for both types mechanical treatment. However, the optimum reduction of water absorption is recorded for mechanical treatment with ball. The water absorption suddenly undergoes breakdown, when the temperatures reached an elevated range between (300°C-

350°C) approximately. Then it increases dramatically at a high temperature range between (350°C-500°C). This outcome emphasizes findings of previous investigations (Wong et al., 2007; Gupta et al., 2012; Al-Bayati et al., 2016), who found that the exposure to high temperatures leads to degradation, breakdown, mass loss and microcracking. The outcomes also revealed that a considerable correlation thoroughly indicates to a strong connection between water absorption and two different mechanical properties as shown in Figure 9 (b). However, there is a high impact from the type of mechanical technique used on the water absorption of CRCA due to the noticeable difference in results. While water absorption through combination acetic acid with mechanical treatments exhibits as a polynomial equation, the behavior of water absorption is a linear equation for combining strong acid and same mechanical treatments.

Figure 10 represents scattering diagram to obtained results and literature findings for water absorption and specific gravity. It is clearly to note that a considerable difference is registered for findings of present study through using combination technique between different treatments and literature outcomes that represent single stage of treatment. This refers to successful utilization of combination technique due to the significant improvement of water absorption and specific gravity. However, aggregate type, origin of RCA and amounts of adhered mortar are still crucial factors that play important role for enhancing RCA properties.

5.2.2 Adhered Mortar Loss

The behavior of adhered mortar loss through combination various treatment methods are investigated in Figures 11 (a & b). For combination between heat and mechanical treatments, it can be observed that there is a significant influence of mechanical treatment type on the adhered mortar removal due to obtaining highly different results as shown in the Figure 10 (a). Additionally, the adhered mortar loss through the use of heat with mechanical method without ball conducts as an exponential equation. Whereas, combining mechanical method with ball and same heat treatment behaves as polynomial equation. However, a high correlation was obtained for both types of mechanical methods with heat treatment. As can be seen in Figure 10 (b), the findings are also demonstrated that the adhered mortar removal for CRCA-2 was behaved as a first order (linear) equation with a considerable regression for both types of mechanical treatments through combination between various acids and mechanical treatments. However, there was a slight difference to adhered mortar loss due to mechanical treatment type.

5.3 Effect of treatment methods on micro properties of CRCA

5.3.1 Porosity

The results of effect of various treatments on porosity are presented in the Figure 12 and Table 4.The outcomes of porosity experiments through heat treatment revealed that the porosity was decreased with rising treatment temperatures and there is a noticeable decrease in the porosity of CRCA between 20°C-250°C as shown in Figure 12. At higher temperatures above 250°C, the porosity percentage was gradually increased, and then the percentage of porosity was sharply increased at temperatures of 350°C and higher, recording a negative impact for heat treatment at elevated temperatures on porosity. The laboratory results of water absorption test emphasizes the success of the heat treatment because the water absorption of a material is highly correlated with the porosity of this material. Whereas, CRCA was suffered from thermal expansion and internal stress due to exposure to high temperatures between 400°C and 500°C which led to severe microcracking of the cement matrix, breakdown and mass loss of concrete particles (Wong et al., 2007; Vieira et al., 2011; Gupta et al., 2012; Al-Bayati et al. 2016) as it is mentioned earlier. Therefore, deterioration condition is mainly responsible for highly increasing the porosity of CRCA.

The experimental outcomes are also demonstrated that a slight improvement on the porosity of CRCA is obtained after various acid treatment types. It is interesting to note that there is a relatively weak influence for acids treatment on the porosity with decrease only 9.2% and 3.8% to HCl and acetic acid respectively as shown in Table 4. However, acid treatment with strong acid appears to be more effective than weak acid for enhancing porosity of CRCA.

5.3.2 Ca/Si ratio

The findings of EDAX analysis for untreated CRCA and treated with different methods are given in Appendix A. The findings represent spectrum analysis for chemical and mineral composition of CRCA through EDAX quantification. Figure 13 and Table 5 appear behavior of atomic Ca/Si ratio through heat treatment and effect of various acid treatments on atomic Ca/Si ratio respectively. The EDAX analysis revealed that there was a highly significant reduction in the Ca/Si ratio with the rising temperatures during heat treatment, as shown in Figure 13. A noticeable decrease was observed in the temperatures range between 20°C and 350°C. By contrast, a slight increase is registered to Ca/Si ratio for heat treatment at 500°C compared with the same ratio at 350°C. It can be interpreted that there is an increase for Ca atoms due to CH decomposition at high temperatures resulting in rising atomic Ca/Si ratio. Thermal Gravimetric Analysis (TGA) studies indicated that the mass loss for RCA material between 420°C and 550°C is correlated with CH decomposition (Al-Bayati et al., 2016). However, a second order equation with considerable regression thoroughly reflects strong relationship and indicates to Ca/Si ratio is highly dependent on heat treatment. Interestingly enough, a considerable reduction of atomic Ca/Si ratio is observed, recording very successful treatment for both types of acid compared with heat treatment. However, there is a significant difference with values of 0.88 and 1.84 for weak and strong acid, respectively, indicating to weak acid is more efficient for enhancing surface microstructure.

5.4 Influence of combination between different treatments on micro properties

5.4.1 Porosity

The results of porosity behavior through combination between heat and acid treatment with both types of short mechanical treatment were diagrammatically analyzed in Figures 14 (a & b). As it is shown in Figure 14 (a), the obtained outcomes reveal that there is a considerable reduction to porosity of CRCA with increasing temperatures that are ranged between (20°C-250°C) for both types mechanical treatment. However, a significant lowering is highly noticeable between 250°C and 350°C, recording the best performance for mechanical treatment with ball. Then, porosity instantaneously undergoes breakdown, when the temperatures reached an elevated range between (300°C-350°C) approximately. Then it increases dramatically at high temperature range between (350°C-500°C).The findings also demonstrated that the porosity behavior through combination of acid treatment types and mechanical treatment was behaved as a linear equation for strong acid and a second order equation for weak acid. A considerable correlation is obtained for both equations though a significant reduction of porosity is registered for combining weak acid and mechanical treatment with ball.

5.4.2 Ca/Si ratio

Figure 15 shows behavior of atomic Ca/Si ratio through heat treatment before and after combination with mechanical treatment with ball. Whereas, Table 6 displays performance of Ca/Si atomic ratio before and after combination between acids and mechanical treatment. The experimental outcomes of the EDAX analysis indicated that a significant difference is highly noticeable to behavior of Ca/Si ratio between heat treatment without combination and its combination with mechanical treatment with ball. It is observed that there is considerable reduction of Ca/Si ratio to status of combination, indicating to big improvement for CRCA microstructure. However, behavior of two cases is a second order equation with a significant regression which refers to a strong relationship between Ca/Si ratio and the techniques of treatment: combination and without combination. The results also demonstrated that a successful treatment for lowering Ca/Si ratio is registered to both types of techniques: without combination (acid treatment only) and combination between acid and mechanical treatment. It is highly interesting to note that a considerable reduction to Ca/Si ratio for weak acid compared with strong acid for both of the different techniques referring that acetic acid seems to be more effective than HCl acid.

5.5 Relationship between different macro properties before and after combination

Figures 16 and 17 demonstrate the relationships among different macro properties of CRCA after various techniques: without combination, combination without/with balls under the influence of heat treatment. The linkage of macro characteristics includes the relation between water absorption and abrasion loss and adhered mortar loss. Complicated and nonlinear (second order equations) relations are obtained that obviously reflect behavior of these characteristics. A significant correlation thoroughly indicates a strong connection among different macro properties, indicating the utilization of successful treatment methods, and there is no negative effect for various treatment techniques on the consistency among different macro characteristics compared to untreated CRCA. In fact, the experimental results confirmed that there is a considerable improvement to different macro properties as was discussed earlier. However, it is observed that there is a slight difference for regression values among different treatment techniques and various macro properties.

5.6 Relationship between different micro properties before and after combination

The relationship between micro characteristics in terms of porosity and Ca/Si ratio is presented in Figure 19. The findings of Ca/Si ratio includes two techniques: without combination (heat treatment) and with combination of two different treatments (heat and mechanical treatment). Whereas, porosity results only relate to the method of mechanical treatment with balls. As can be seen, complicated and nonlinear equations are obtained that evidently describe behavior of these properties. It is interesting to note that a slight reduction is clearly shown by the regression value with regards to the technique with combination compared with the other method, indicating a small negative impact for this method. However, the correlation that is recorded for different techniques certainly refers to a good relation between these micro properties.

5.7 Relationship between micro and macro properties before and after combination

5.7.1 Relation between porosity and various macro properties

Figures 20 to 22 demonstrate the relation between micro properties; namely porosity, and various macro characteristics of CRCA including water absorption, abrasion loss and adhered mortar loss under various techniques. As it is shown in figures 20 (a) and 20 (b), a considerable regression is obtained for various techniques, referring to a strong relation between porosity and water absorption, and successful treatment methods for enhancing different characteristics of CRCA without any negative impacts on consistency between various properties. However, it is interesting to note that the behaviour of the relation between porosity and water absorption completely transforms from a polynomial (second order) equation to exponential and logarithmic equations for no combination and combination with mechanical treatment with balls technique respectively. The obtained findings also revealed that a significant relationship is registered between porosity and two macro properties in terms of abrasion loss and adhered mortar loss as shown by a considerable correlation as can be seen in figures 21 and 22. It is notable that a second order equation reflects the behaviour of the relation of various characteristics using different techniques including no combination method, combination with mechanical treatment without balls and combination with mechanical treatment with balls.

5.7.2 Relation between Ca/Si atomic ratio and various macro properties

Figures 23 and 24 indicate the relation between micro characteristics in terms of Ca/Si atomic ratio and different macro properties of CRCA including adhered mortar loss and abrasion loss under various techniques. Nonlinear relationships are obtained for different methods that obviously reflect the behaviour of these diverse characteristics. As shown in figures 23 (a) and 23 (b), a slight increase in regression values is recorded for combination with mechanical treatment with balls compared with combination with the same mechanical method without balls, resulting in more improving of correlation between Ca/Si ratio and adhered mortar loss. Interestingly, the behaviour of the relation between Ca/Si and adhered mortar loss is transformed from an exponential to a polynomial equation through utilizing mechanical treatment with balls compared to the without balls technique. The outcomes also demonstrated that there is a significant regression that completely reflects a strong relationship between Ca/Si atomic ratio and abrasion loss for various techniques, indicating there is no negative influence for different combination techniques on the relation between micro and macro characteristics of CRCA.

Conclusions:

- Separately, among different treatment methods, heat treatment type at 350°C has a maximum influence for enhancing various macro and micro properties of CRCA including water absorption, specific gravity, abrasion loss and atomic Ca/Si ratio. It was also concluded that heat treatment at 250°C has an optimum impact on porosity improvement, whereas weak acid has better impact on adhered mortar enhancement among the various treatment types.
- Nevertheless, it is highly recommended to use heat treatment type at temperatures between 300°C-350°C because of the noticeable negative effects of higher temperatures on different macro and micro CRCA characteristics. The aggregate suffers from thermal expansion followed by internal stresses due to exposure to high temperature between 350°C and 500°C resulting in degradation, breakdown and mass loss of aggregate.
- The acid treatment at low concentration is an effective technique to enhance the macro and micro characteristics of CRCA depending on the acid type due to the corrosive influence on the attached mortar. However, it is interesting to conclude that using weak acid is more effective than strong acid to enhance macro and micro properties in terms of abrasion loss, adhered mortar loss and atomic Ca/Si ratio, whereas acid treatment with strong acid appears to be more efficient in improving water absorption and porosity.
- The utilization of combination method between different treatment types is a highly successful technique for improving macro and micro characteristics of CRCA compared with separate (single) treatments due to a considerable difference in the findings of the present study and even with literature findings.
- It is concluded that among the various methods, the combination between acetic acid treatment and short mechanical method with steel balls exhibits the best performance by reducing the water absorption by 36.9%. This was followed by integration of thermal treatment at 350°C and short mechanical treatment with steel balls by 26.7%, then the

combination of strong acid and the same mechanical process by 23%, compared to untreated CRCA.

- Macro properties of CRCA including water absorption and abrasion loss and adhered mortar loss are strongly correlated, and micro characteristics in terms of porosity and atomic Ca/Si ratio are also significantly connected, although the behaviours of these characteristics are complicated and nonlinear relationships. Interestingly, it is concluded that there is no negative effect for various treatment techniques on the consistency among different macro and micro characteristics compared to untreated CRCA.
- Various macro characteristics of CRCA in terms of water absorption and abrasion loss and adhered mortar loss are strongly related with different micro properties including porosity and atomic Ca/Si ratio.

Acknowledgement

The authors gratefully acknowledge the funding provided by Ministry of Higher Education and Scientific Research/Iraq through Iraqi Scholarship/Doctoral Program. The authors are also grateful to Steed and Evans Ltd in the Region of Waterloo, Ontario for providing Recycled Concrete Aggregate material. A special thanks to Dr. Nafiseh Moghimi in the Waterloo Advanced Technology Laboratory (WATLab)/University of Waterloo for her substantial support throughout SEM/EDAX tests. Her effort, advice and patience are greatly appreciated.

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Table 1. Macro and some physical properties of untreated CRCA

CRCA	Bulk Relative Density (BRD) ASTM C 127	Bulk Relative Density (SSD) ASTM C 127	Absorption, % ASTM C 127	Adhered Mortar, %		Micro-Deval Abrasion Loss, %ASTMD6928	Fractured Particles,% ASTM D5821	Aggregate Crushing Value BS 812-110	Flat & Elongated,% LS-608
				With steel ball	Without steel ball				
	2.421	2.512	3.74	2.53	1.08	16.03	95.72	23.28	0.44

Table 2: Specific gravity and absorption before and after treatments of CRCA

CRCA Treatment/ Property	Bulk Relative Density (BRD)	Apparent Specific Gravity	Bulk Relative Density (SSD)	Absorption*, %
CRCA untreated	2.421	2.662	2.512	3.74
CRCA heat at 250°C	2.436	2.668	2.523	3.57
CRCA heat at 350°C	2.454	2.672	2.536	3.32
CRCA heat at 500°C	2.409	2.659	2.503	3.90
CRCA soaking in C2H4O2	2.431	2.663	2.518	3.51
CRCA soaking in HCl	2.452	2.671	2.534	3.35

* The MTO OPSS 1003 specification limit is 2.0% Max.

Table 3: Specific gravity and water absorption of CRCA before and after treatments followed by short mechanical treatment with and without steel ball

RCA Treatment/ Property	Bulk Relative Density (BRD)			Apparent Specific Gravity			Bulk Relative Density (SSD)			Absorption****, %		
	B.M.T*	A.M.T Wt.B**.	A.M.T W.B***.	B.M.T	A.M.T Wt.B.	A.M.T W.B.	B.M.T	A.M.T Wt.B.	A.M.T W.B.	B.M.T	A.M.T Wt.B.	A.M.T W.B.
CRCA without treated	2.421	2.432	2.453	2.662	2.663	2.664	2.512	2.519	2.532	3.74	3.58	3.23
CRCA heated at 250°C	2.436	2.441	2.477	2.668	2.671	2.673	2.523	2.527	2.551	3.57	3.52	2.96
CRCA heated at 350°C	2.454	2.497	2.524	2.672	2.710	2.712	2.536	2.576	2.594	3.32	3.14	2.74
CRCA heated at 500°C	2.409	2.426	2.441	2.659	2.661	2.662	2.503	2.514	2.524	3.90	3.64	3.41
CRCA soaking in $C_2H_4O_2$	2.431	2.450	2.551	2.663	2.665	2.715	2.518	2.531	2.612	3.51	3.30	2.36
CRCA soaking in HCl	2.452	2.461	2.484	2.671	2.674	2.676	2.534	2.540	2.556	3.35	3.25	2.88

B.M.T*= before mechanical treatment, A.M.T. Wt. B**= after mechanical treatment without steel ball, A.M.T. W.B***= after mechanical treatment with steel ball. **** The MTO OPSS 1003 specification limit is 2.0% Max.

Table 4. Porosity of CRCA before and after various acid treatments.

CRCA Treatment/ Property	Porosity, %
CRCA untreated	9.05
CRCA soaking in $C_2H_4O_2$	8.71
CRCA soaking in HCl	8.22

Table 5. Ca/Si atomic ratio of CRCA before and after various acid treatments.

CRCA Treatment/ Property	Ca/Si atomic ratio
CRCA untreated	5.59
CRCA soaking in $C_2H_4O_2$	0.88
CRCA soaking in HCl	1.84

Table 6. Ca/Si atomic ratio before and after combination between acids and mechanical treatment

CRCA Treatment/ Property	Ca/Si atomic ratio before combination	Ca/Si atomic ratio after combination
CRCA untreated	5.59	5.59
CRCA soaking in $C_2H_4O_2$	0.88	0.37
CRCA soaking in HCl	1.84	1.09

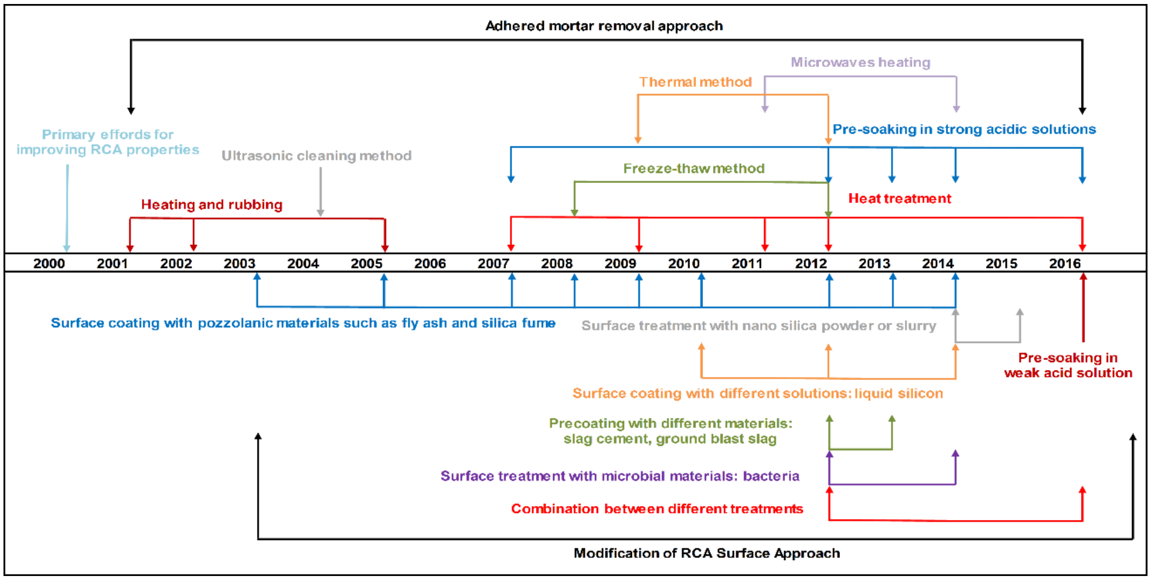


Figure 1: Schematic diagram of various treatment methods for enhancing physical properties of RCA in the literature since 2000 until the present time.

Figure 2: Optical image of CRCA

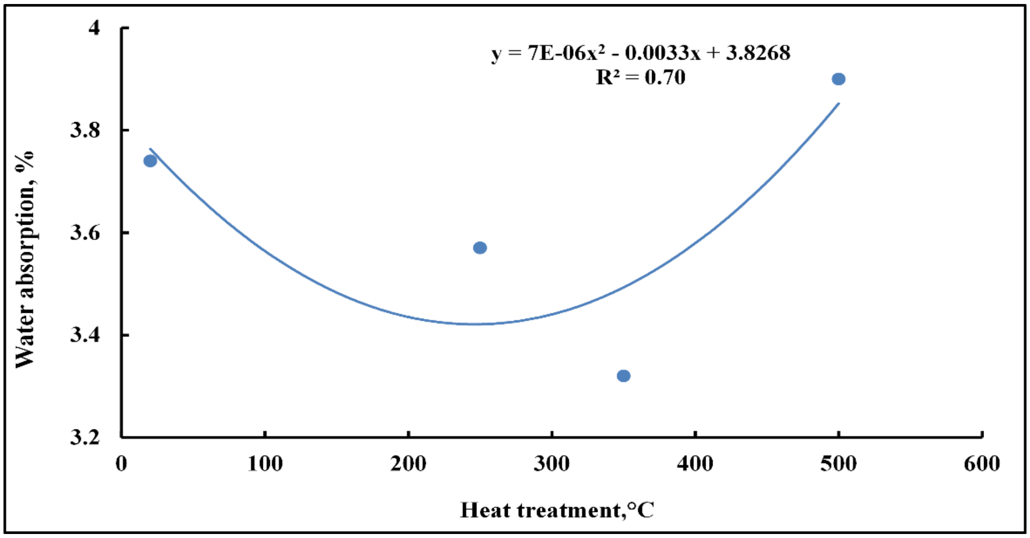


Figure 3: Water absorption through heat treatment

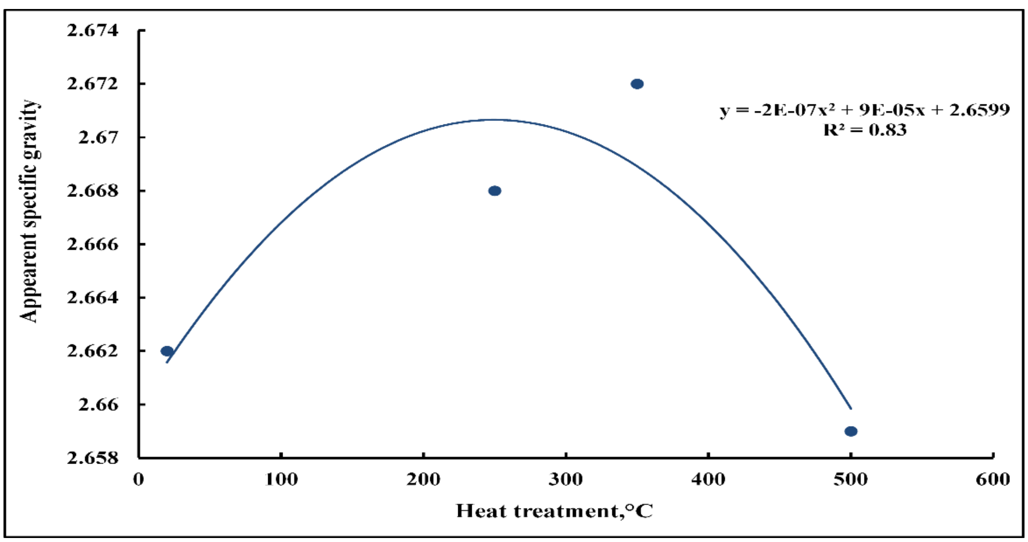


Figure 4. Apparent specific gravity through heat treatment

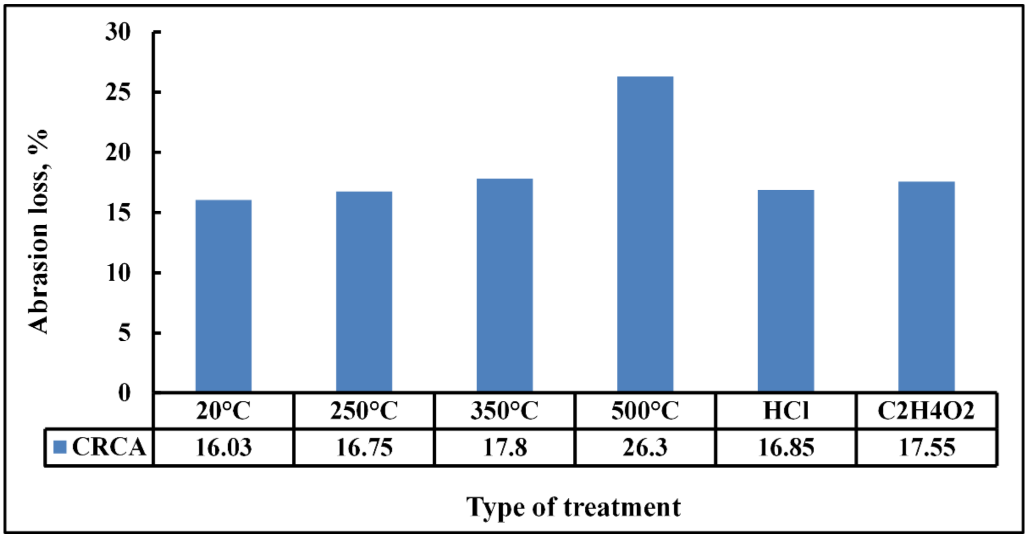


Figure 5. Abrasion loss with different treatments

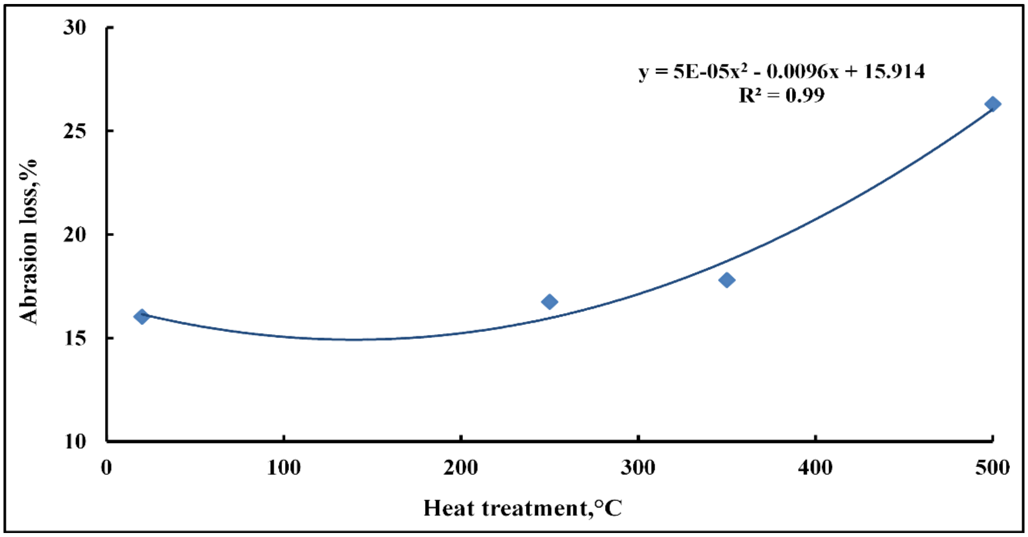


Figure 6: Abrasion loss behavior through heat treatment

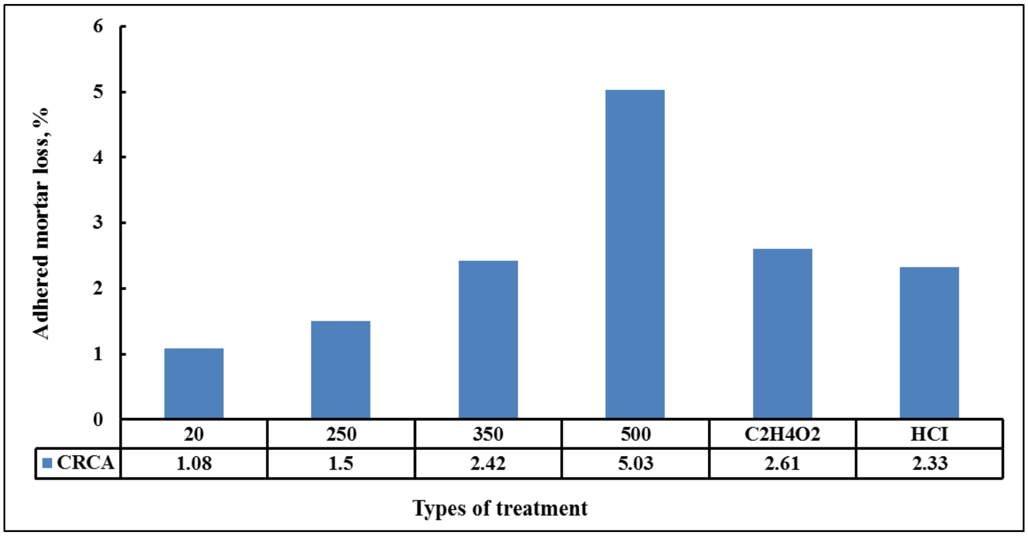


Figure 7: Adhered mortar loss with different treatment

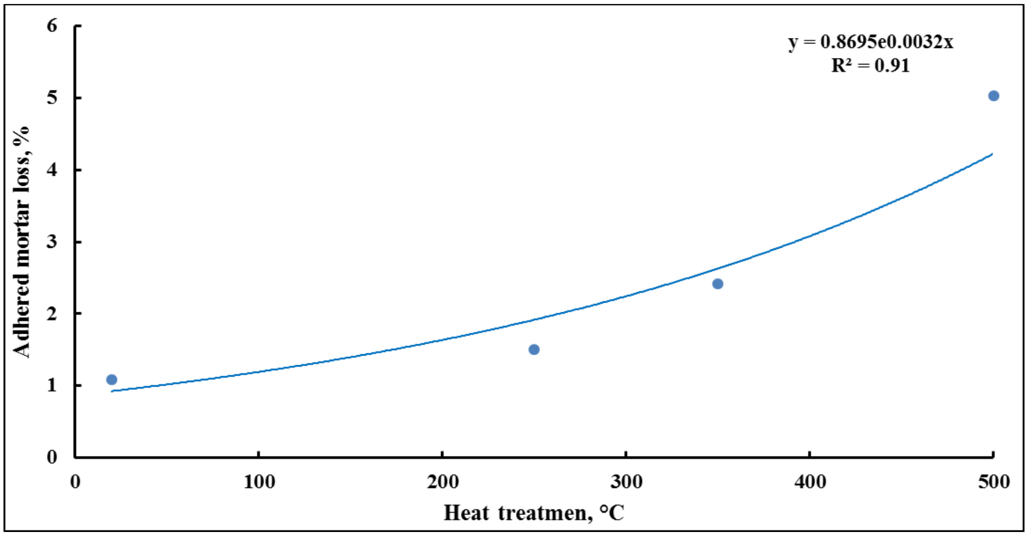
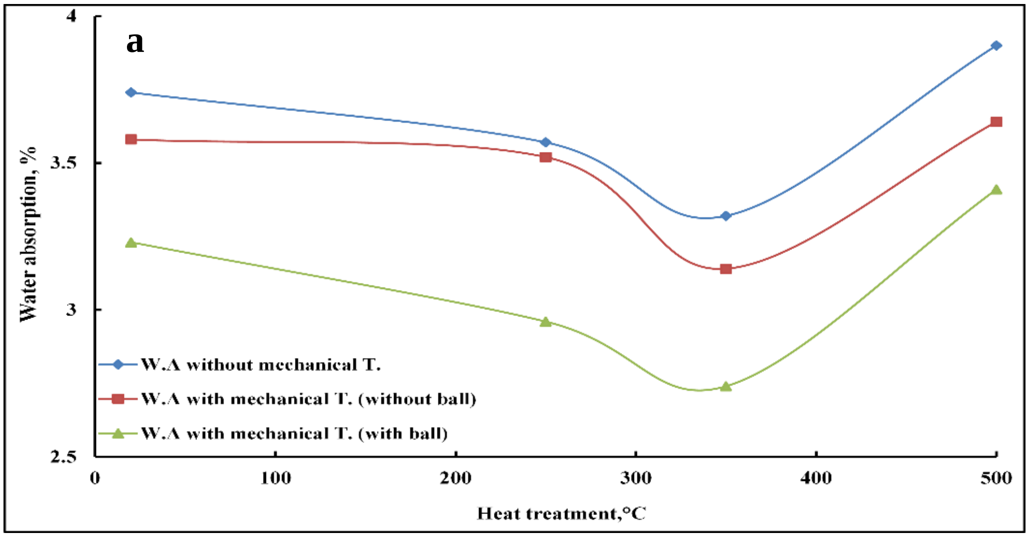


Figure 8: Adhered mortar loss behavior through heat treatments



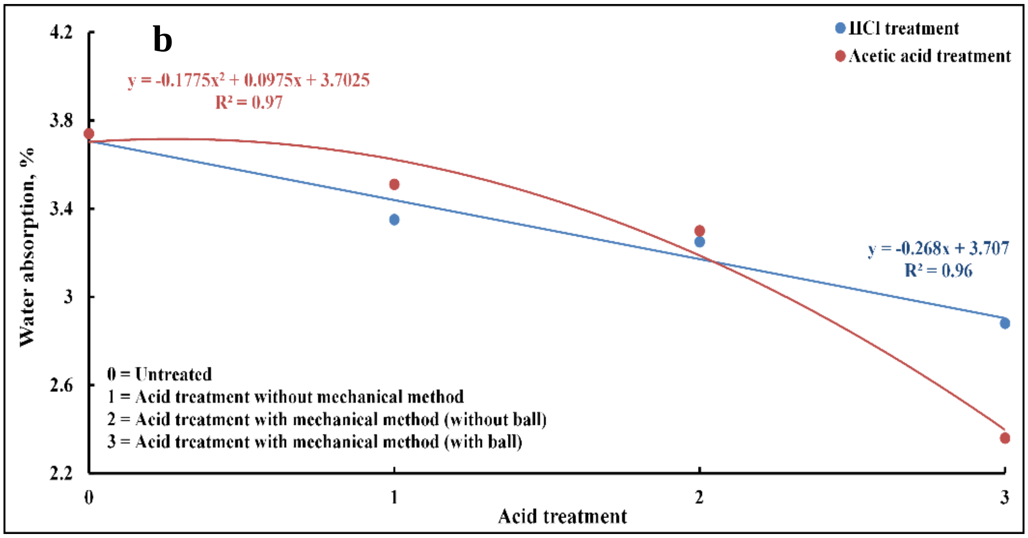


Figure 9: Water absorption behavior through: - a: heat & mechanical T., b: acid & mechanical T.

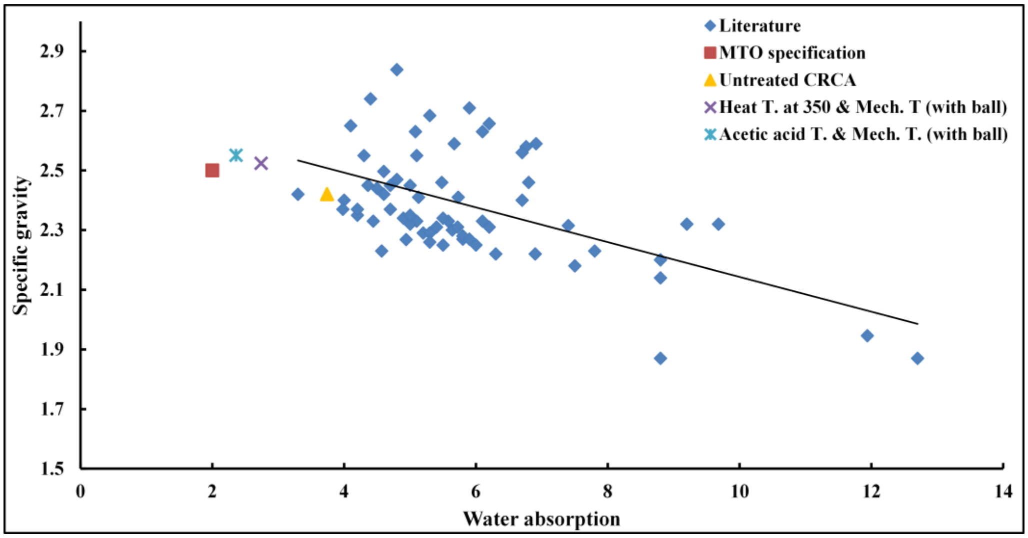
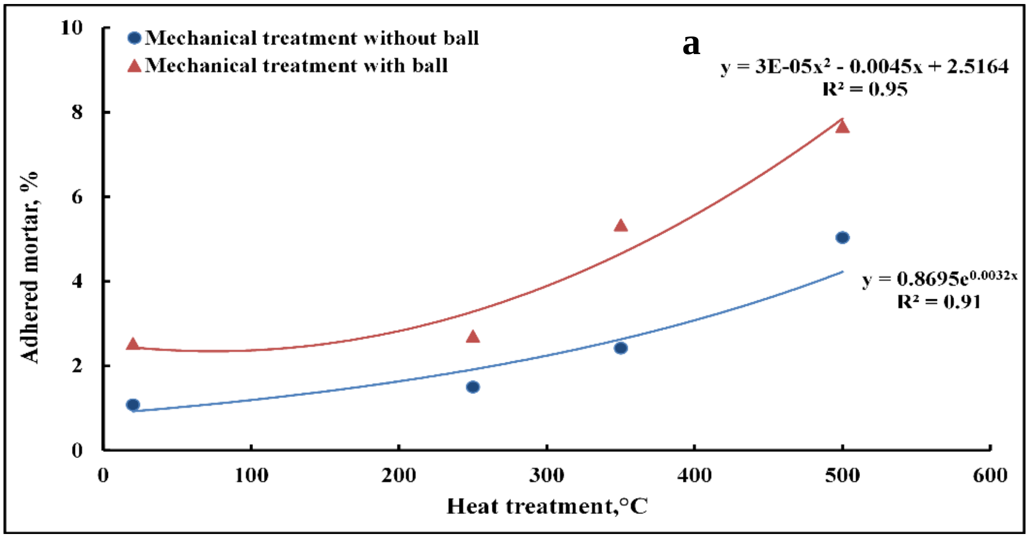


Figure 10: Scattering diagram for the obtained results after combination of various treatments & literature findings



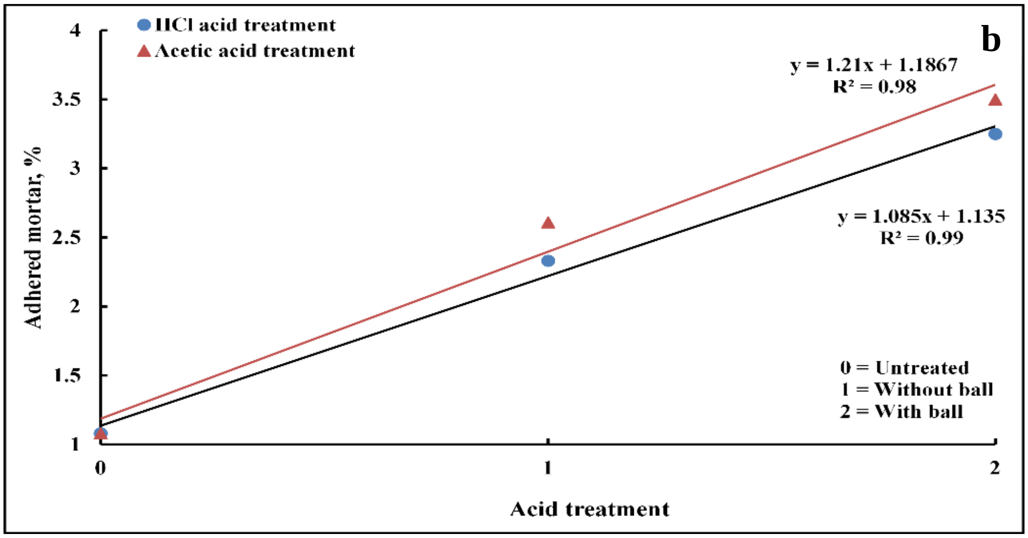


Figure 11: Adhered mortar loss through combination: - a: heat with mechanical T., b: acid with mechanical T. to CRCA

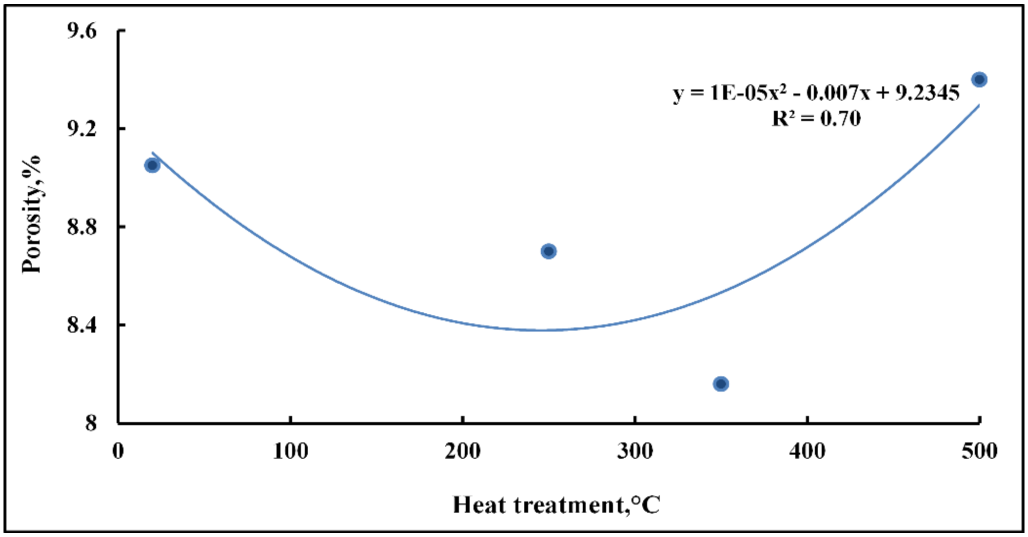


Figure 12: Porosity behavior through heat treatment

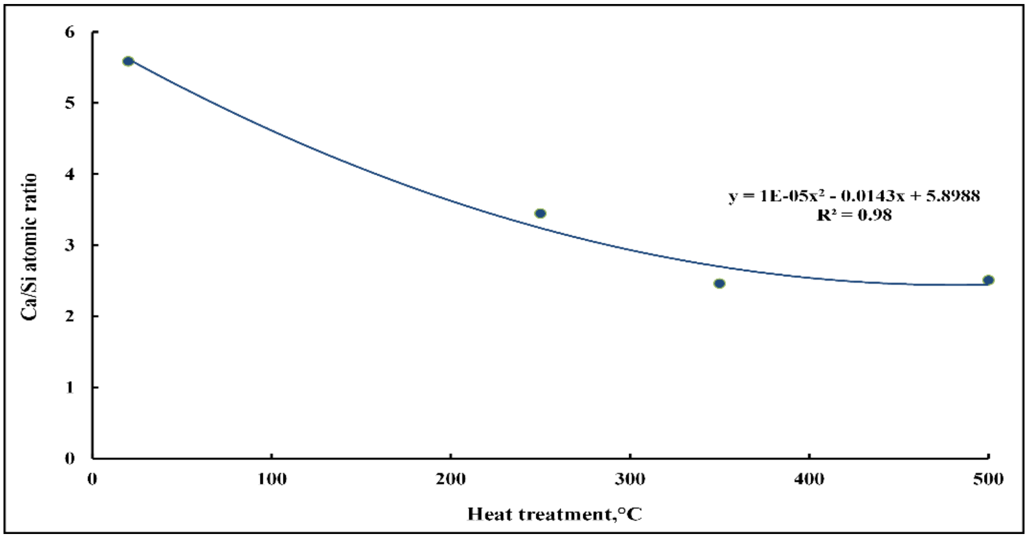
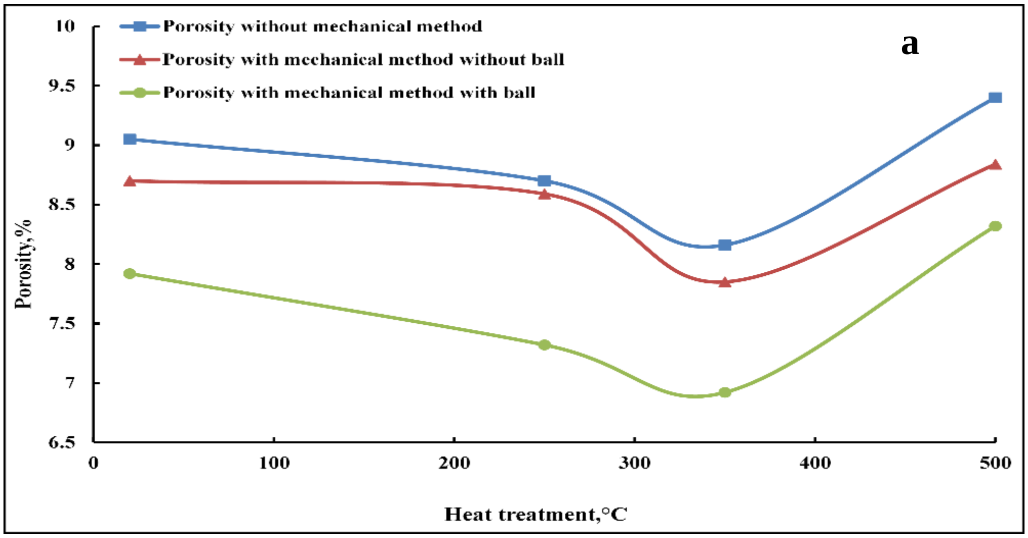


Figure 13: Behavior of Ca/Si atomic ratio through heat treatment



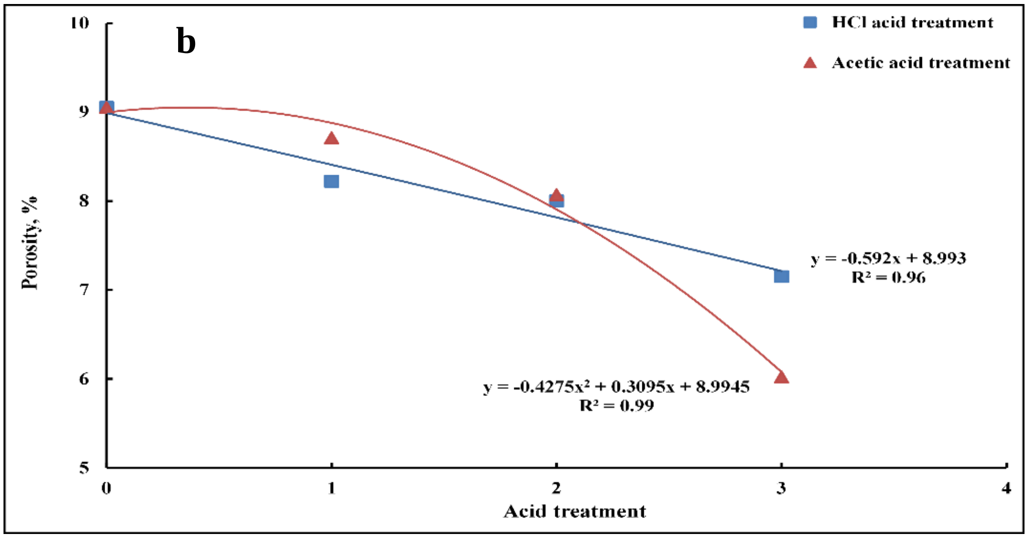


Figure 14: Porosity behavior through combination: - a: heat with mechanical T., b: acid with mechanical T.

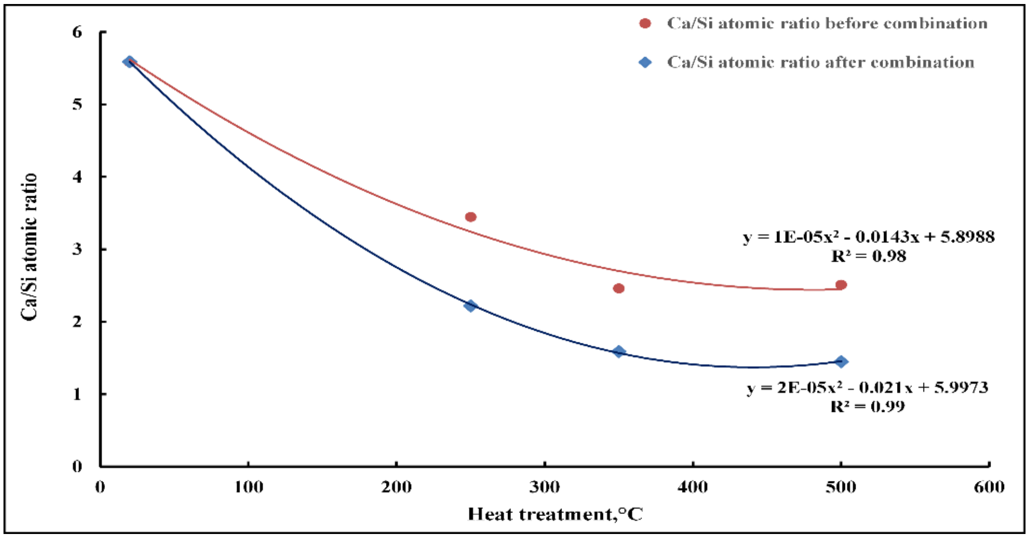


Figure 15: Behavior of Ca/Si ratio before and after combination

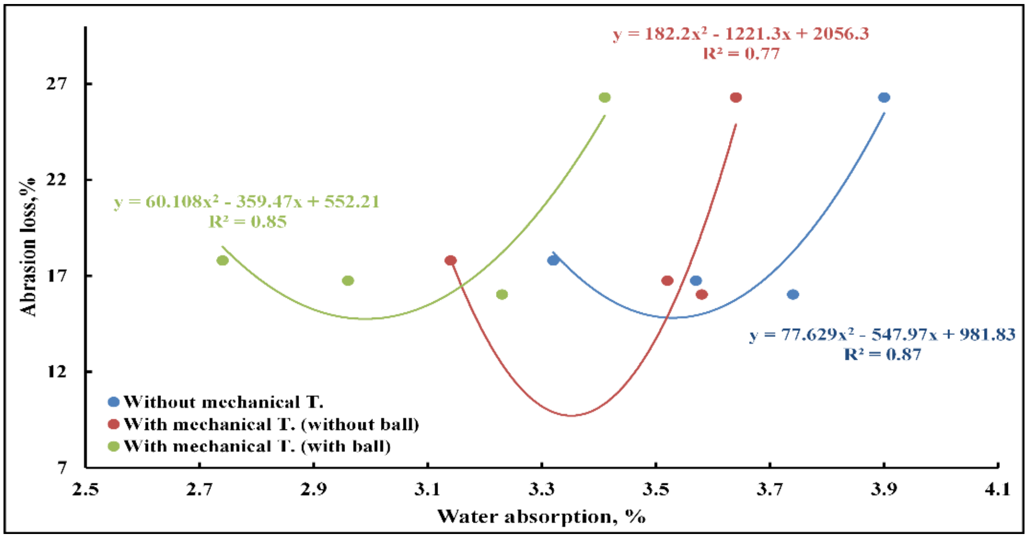
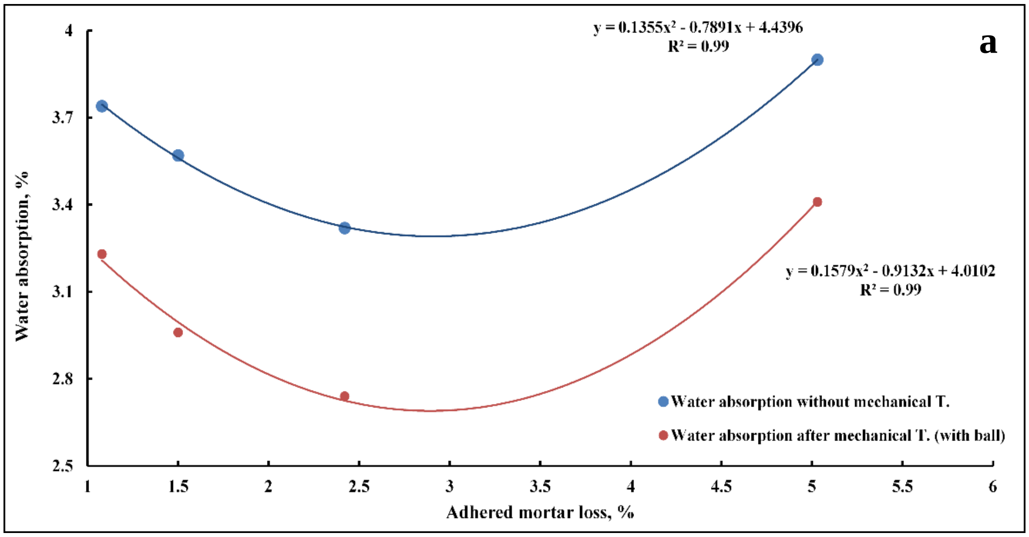


Figure 16: Relation between water absorption in different cases and abrasion loss



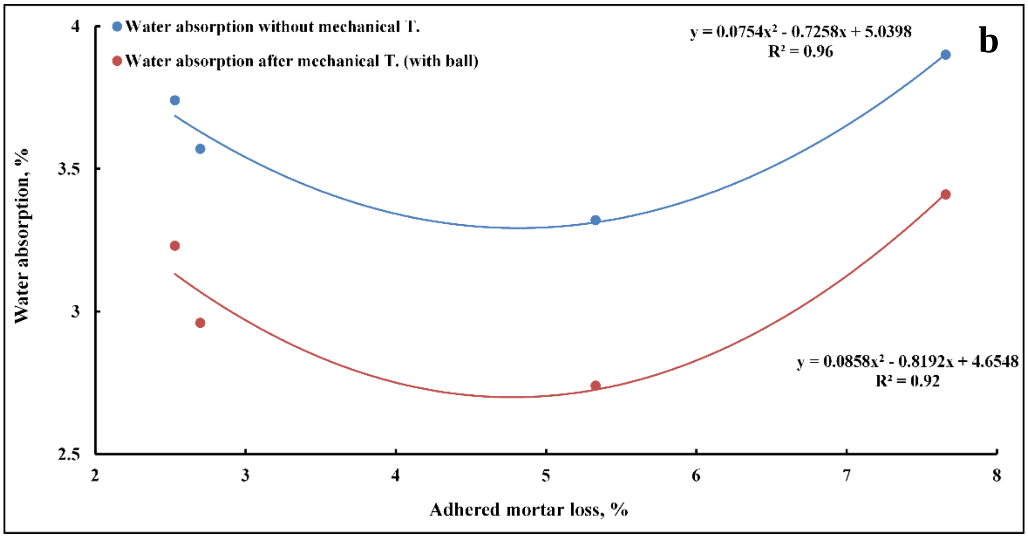


Figure 17: Relation between water absorption in different cases and adhered mortar loss a: without ball, b: with ball

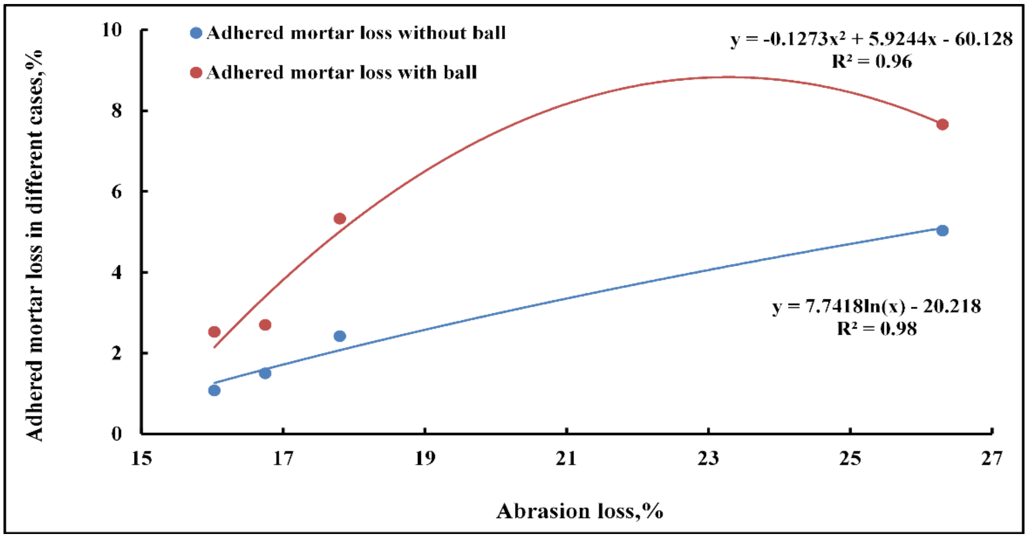


Figure 18: Relation between adhered mortar in different cases and abrasion loss

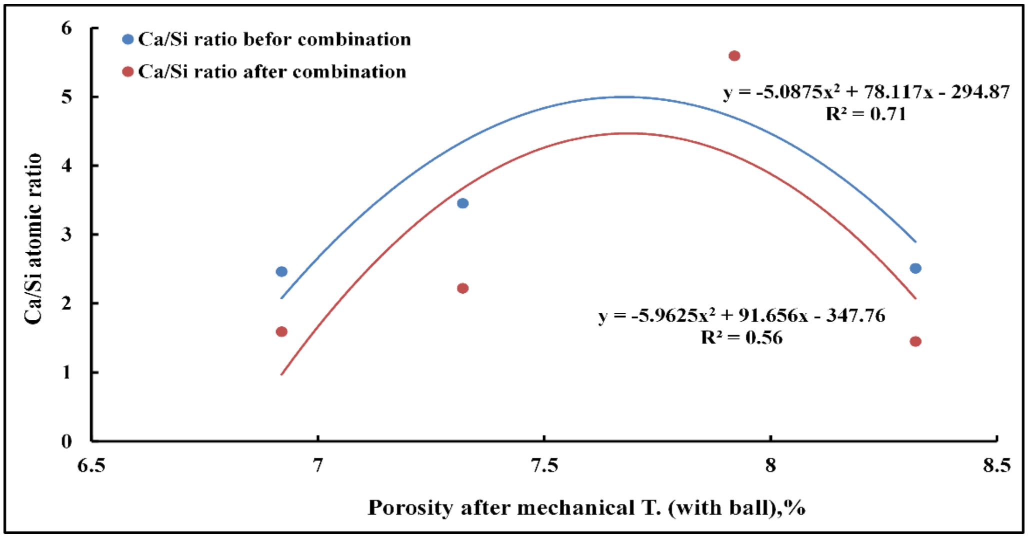
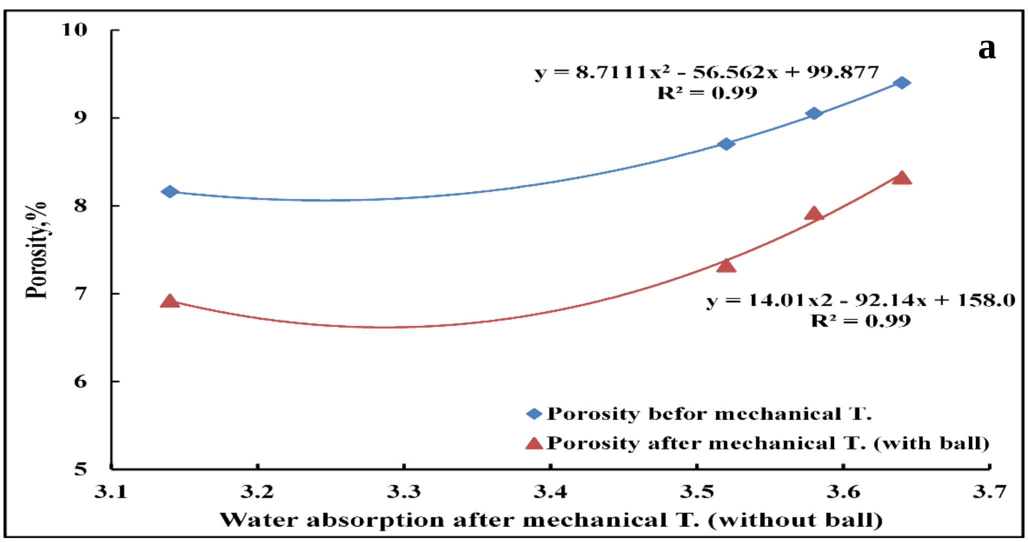


Figure 19: Relation between Ca/Si atomic ratio at various techniques and porosity with mechanical with ball



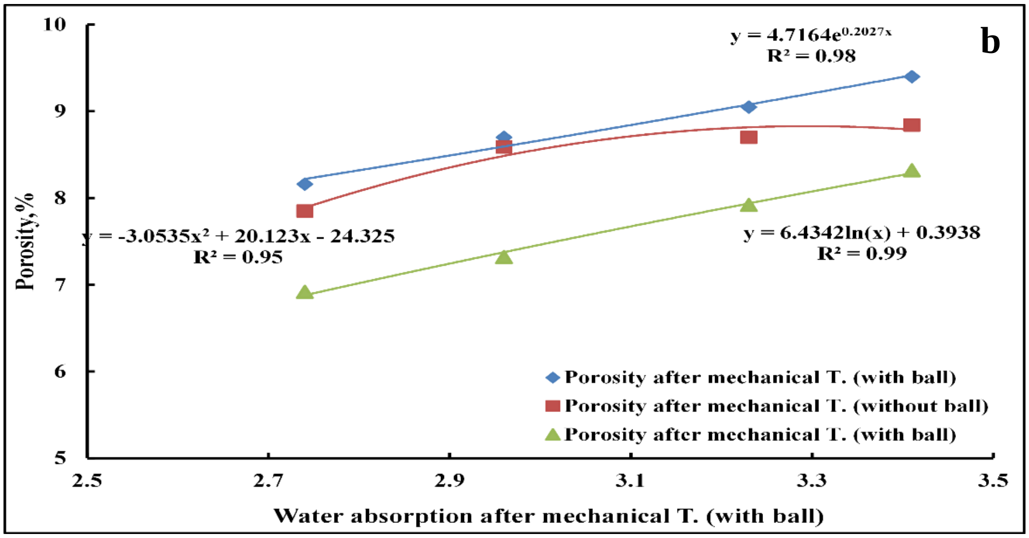


Figure 20: Relation between porosity at various techniques and water absorption: a: without ball, b: with ball

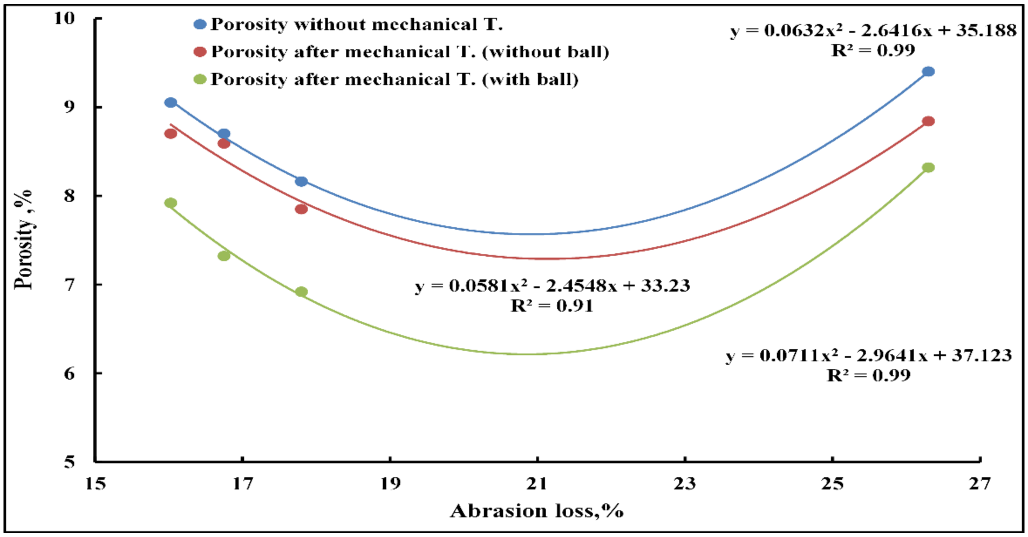
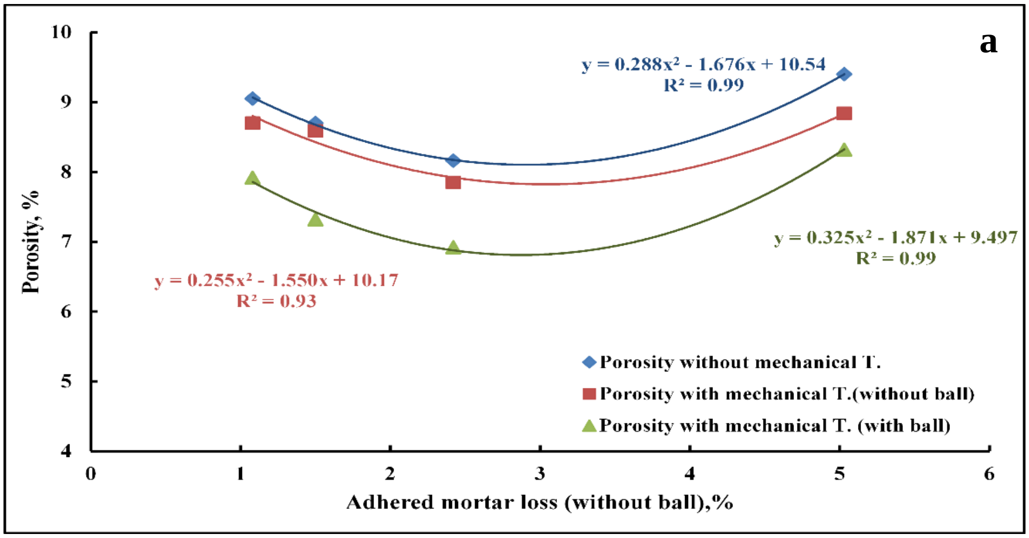


Figure 21: Relation between porosity and abrasion loss



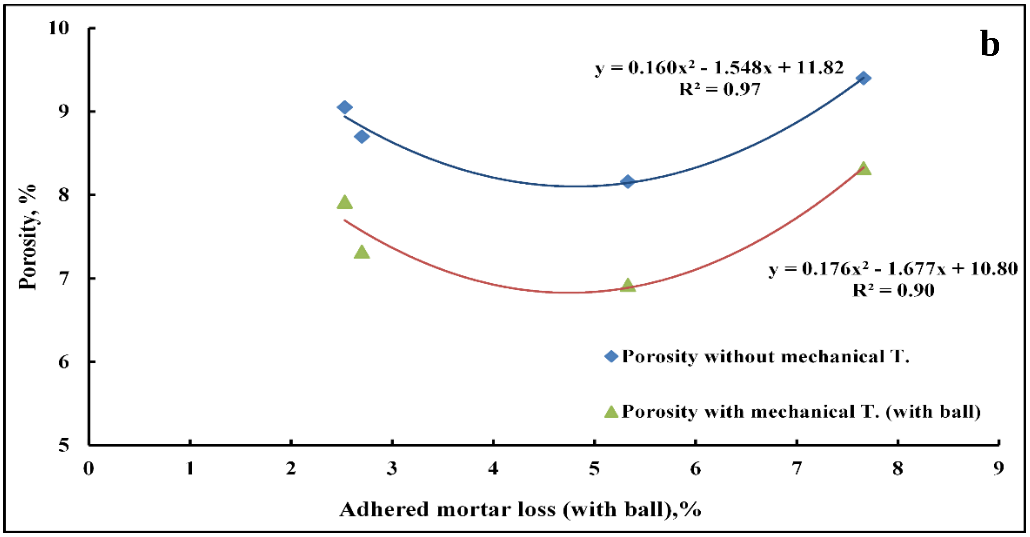


Figure 22: Relation between porosity and adhered mortar loss: a: without ball, b: with ball

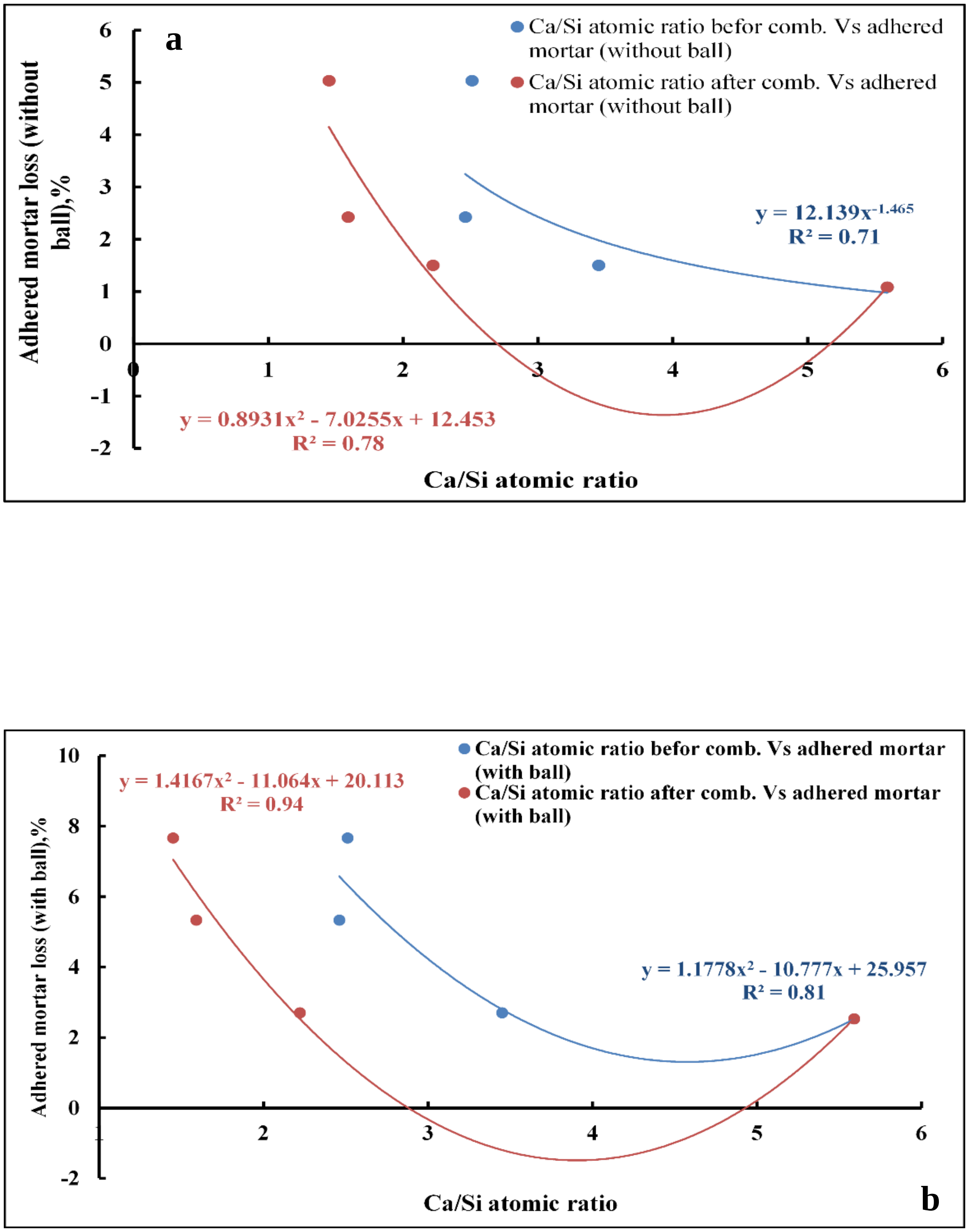


Figure 23: Relation between Ca/Si atomic ratio and adhered mortar loss: a: without ball, b: with ball

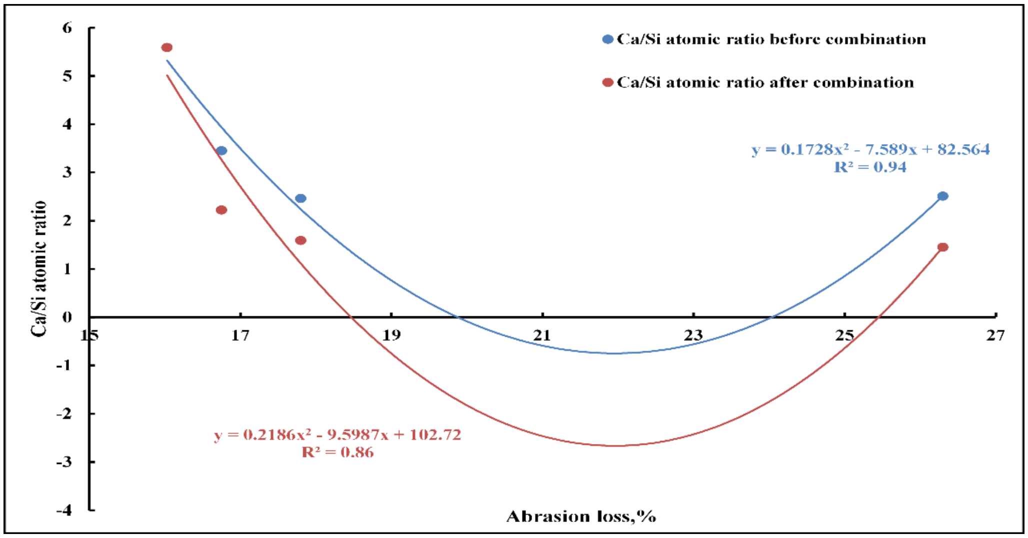
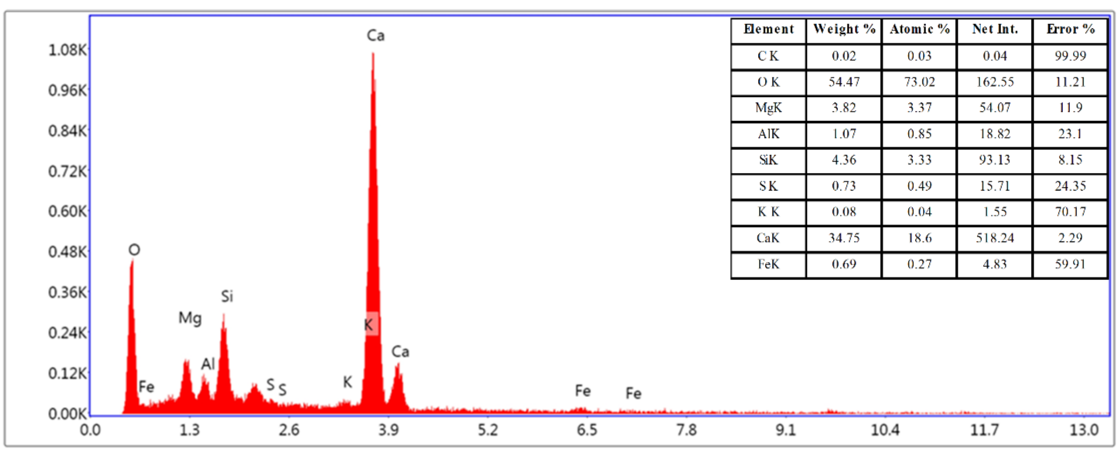


Figure 24: Relation between Ca/Si atomic ratio and abrasion loss

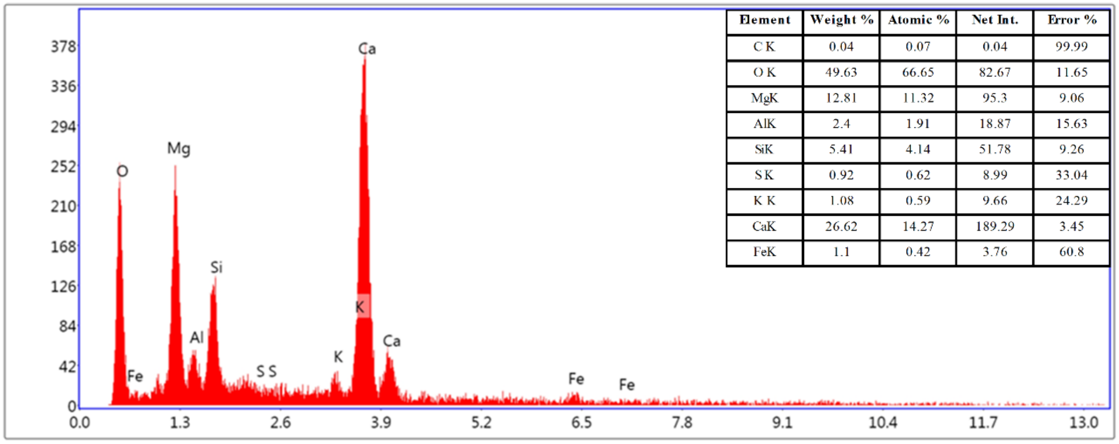
Appendix A



Element	Weight %	Atomic %	Net Int.	Error %
C K	0.02	0.03	0.04	99.99
O K	54.47	73.02	162.55	11.21
MgK	3.82	3.37	54.07	11.9
AlK	1.07	0.85	18.82	23.1
SiK	4.36	3.33	93.13	8.15
S K	0.73	0.49	15.71	24.35
K K	0.08	0.04	1.55	70.17
CaK	34.75	18.6	518.24	2.29
FeK	0.69	0.27	4.83	59.91

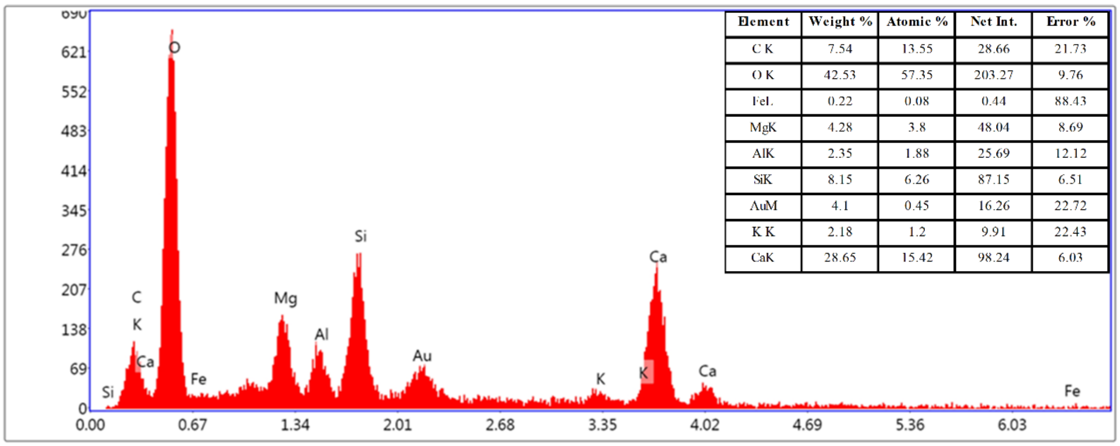
Lsec: 27.7 0 Cnts 0.000 keV Det: Apollo XL-SDD Det

Figure A-1: EDAX for untreated before combination



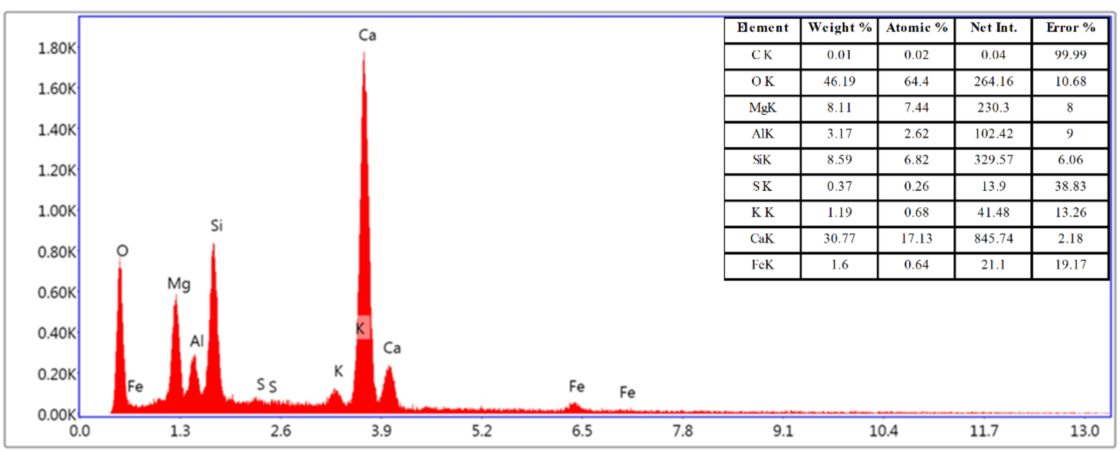
Element	Weight %	Atomic %	Net Int.	Error %
C K	0.04	0.07	0.04	99.99
O K	49.63	66.65	82.67	11.65
MgK	12.81	11.32	95.3	9.06
AlK	2.4	1.91	18.87	15.63
SiK	5.41	4.14	51.78	9.26
S K	0.92	0.62	8.99	33.04
K K	1.08	0.59	9.66	24.29
CaK	26.62	14.27	189.29	3.45
FeK	1.1	0.42	3.76	60.8

Figure A-2: EDAX at 250°C before combination



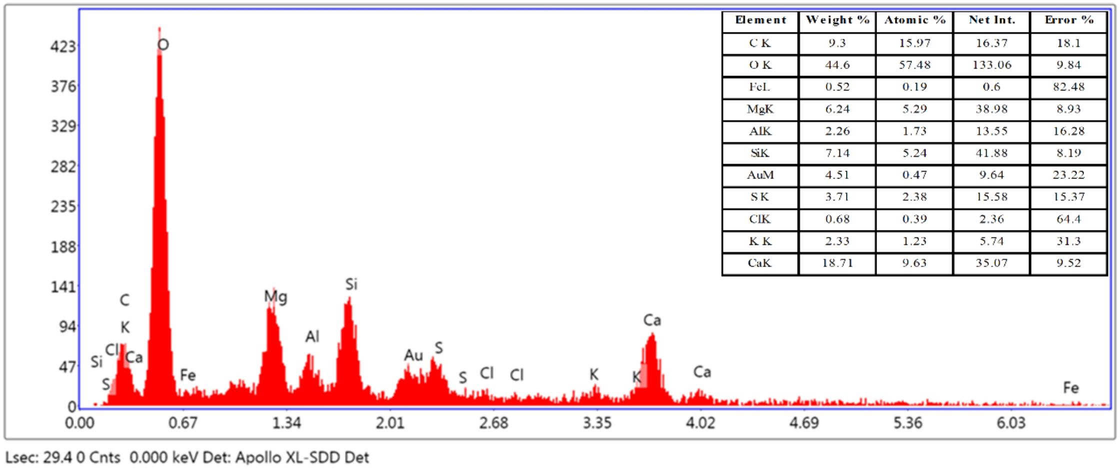
Element	Weight %	Atomic %	Net Int.	Error %
C K	7.54	13.55	28.66	21.73
O K	42.53	57.35	203.27	9.76
FeL	0.22	0.08	0.44	88.43
MgK	4.28	3.8	48.04	8.69
AlK	2.35	1.88	25.69	12.12
SiK	8.15	6.26	87.15	6.51
AuM	4.1	0.45	16.26	22.72
K K	2.18	1.2	9.91	22.43
CaK	28.65	15.42	98.24	6.03

Figure A-3: EDAX at 350°C before combination



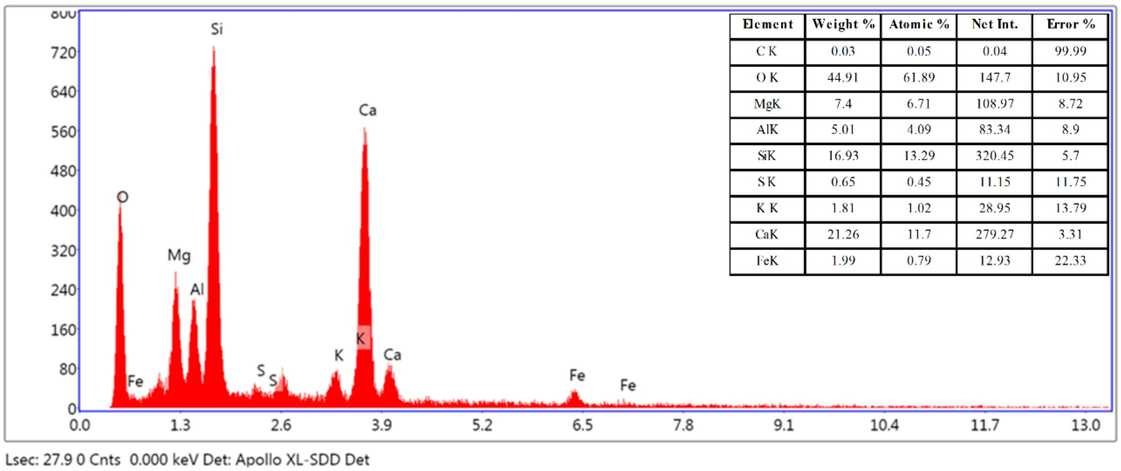
Element	Weight %	Atomic %	Net Int.	Error %
C K	0.01	0.02	0.04	99.99
O K	46.19	64.4	264.16	10.68
MgK	8.11	7.44	230.3	8
AlK	3.17	2.62	102.42	9
SiK	8.59	6.82	329.57	6.06
S K	0.37	0.26	13.9	38.83
K K	1.19	0.68	41.48	13.26
CaK	30.77	17.13	845.74	2.18
FeK	1.6	0.64	21.1	19.17

Figure A-4: EDAX at 500°C before combination



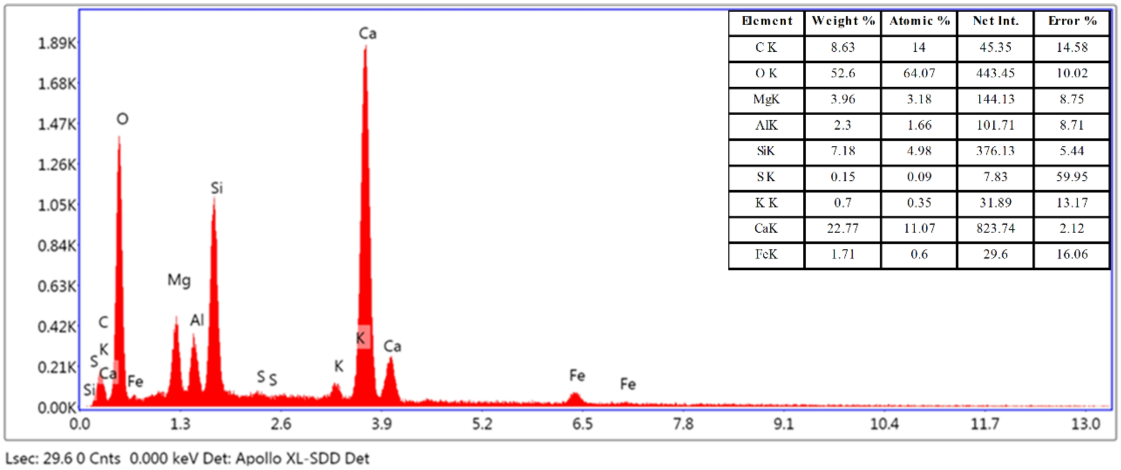
Element	Weight %	Atomic %	Net Int.	Error %
C K	9.3	15.97	16.37	18.1
O K	44.6	57.48	133.06	9.84
FeL	0.52	0.19	0.6	82.48
MgK	6.24	5.29	38.98	8.93
AlK	2.26	1.73	13.55	16.28
SiK	7.14	5.24	41.88	8.19
AuM	4.51	0.47	9.64	23.22
S K	3.71	2.38	15.58	15.37
ClK	0.68	0.39	2.36	64.4
K K	2.33	1.23	5.74	31.3
CaK	18.71	9.63	35.07	9.52

Figure A-5: EDAX with HCl acid treatment before combination



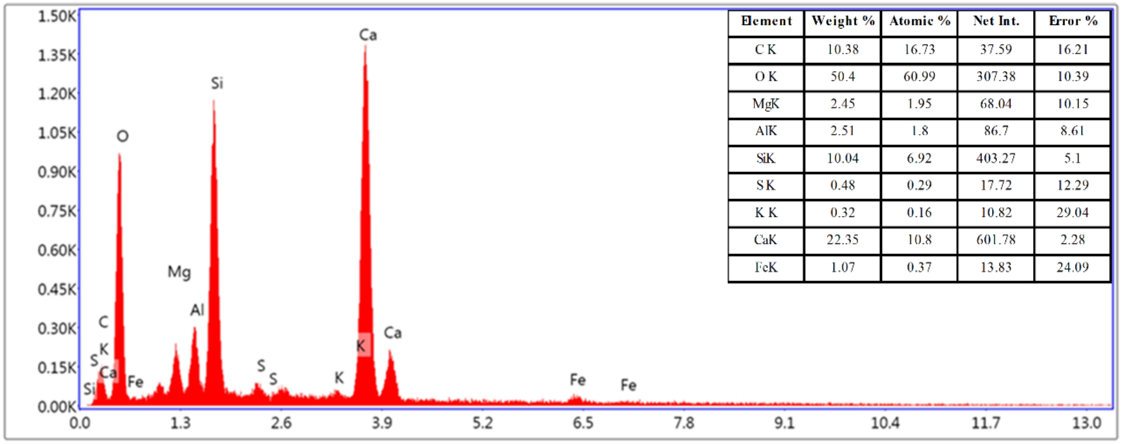
Element	Weight %	Atomic %	Net Int.	Error %
C K	0.03	0.05	0.04	99.99
O K	44.91	61.89	147.7	10.95
MgK	7.4	6.71	108.97	8.72
AlK	5.01	4.09	83.34	8.9
SiK	16.93	13.29	320.45	5.7
S K	0.65	0.45	11.15	11.75
K K	1.81	1.02	28.95	13.79
CaK	21.26	11.7	279.27	3.31
FeK	1.99	0.79	12.93	22.33

Figure A-6: EDAX with acetic acid treatment before combination



Element	Weight %	Atomic %	Net Int.	Error %
C K	8.63	14	45.35	14.58
O K	52.6	64.07	443.45	10.02
MgK	3.96	3.18	144.13	8.75
AlK	2.3	1.66	101.71	8.71
SiK	7.18	4.98	376.13	5.44
S K	0.15	0.09	7.83	59.95
K K	0.7	0.35	31.89	13.17
CaK	22.77	11.07	823.74	2.12
FeK	1.71	0.6	29.6	16.06

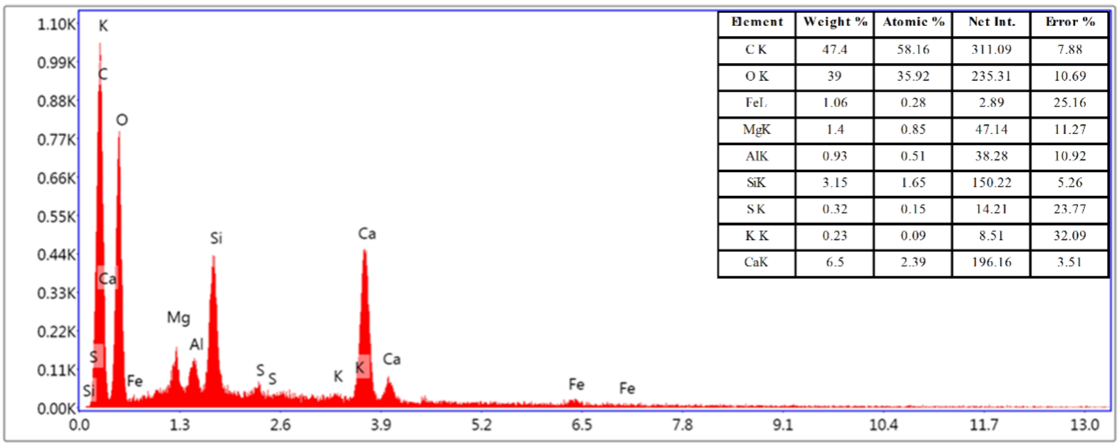
Figure A-7: EDAX at 250°C heat treatment after combination



Element	Weight %	Atomic %	Net Int.	Error %
C K	10.38	16.73	37.59	16.21
O K	50.4	60.99	307.38	10.39
MgK	2.45	1.95	68.04	10.15
AlK	2.51	1.8	86.7	8.61
SiK	10.04	6.92	403.27	5.1
S K	0.48	0.29	17.72	12.29
K K	0.32	0.16	10.82	29.04
CaK	22.35	10.8	601.78	2.28
FeK	1.07	0.37	13.83	24.09

Lsec: 29.6 0 Cnts 0.000 keV Det: Apollo XL-SDD Det

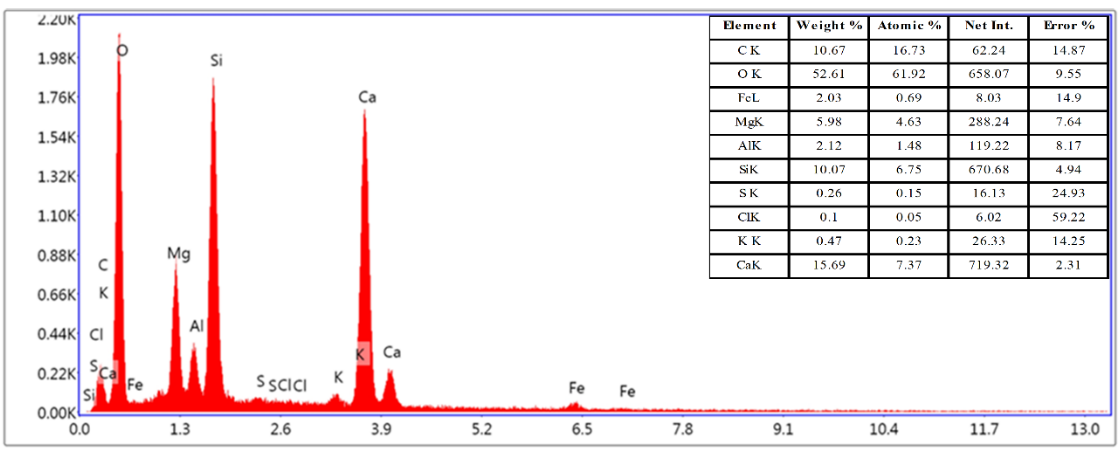
Figure A-8: EDAX at 350°C heat treatment after combination



Element	Weight %	Atomic %	Net Int.	Error %
C K	47.4	58.16	311.09	7.88
O K	39	35.92	235.31	10.69
FeL	1.06	0.28	2.89	25.16
MgK	1.4	0.85	47.14	11.27
AlK	0.93	0.51	38.28	10.92
SiK	3.15	1.65	150.22	5.26
S K	0.32	0.15	14.21	23.77
K K	0.23	0.09	8.51	32.09
CaK	6.5	2.39	196.16	3.51

Lsec: 29.6 0 Cnts 0.000 keV Det: Apollo XL-SDD Det

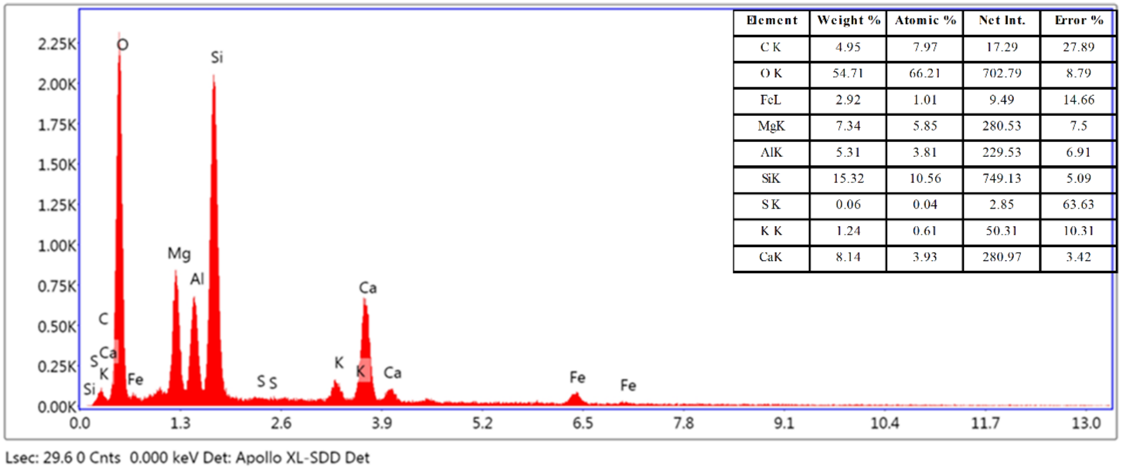
Figure A-9: EDAX at 500°C heat treatment after combination



Element	Weight %	Atomic %	Net Int.	Error %
C K	10.67	16.73	62.24	14.87
O K	52.61	61.92	658.07	9.55
FeL	2.03	0.69	8.03	14.9
MgK	5.98	4.63	288.24	7.64
AlK	2.12	1.48	119.22	8.17
SiK	10.07	6.75	670.68	4.94
S K	0.26	0.15	16.13	24.93
ClK	0.1	0.05	6.02	59.22
K K	0.47	0.23	26.33	14.25
CaK	15.69	7.37	719.32	2.31

Lsec: 29.6 0 Cnts 0.000 keV Det: Apollo XL-SDD Det

Figure A-10: EDAX with HCl acid treatment after combination



Element	Weight %	Atomic %	Net Int.	Error %
C K	4.95	7.97	17.29	27.89
O K	54.71	66.21	702.79	8.79
FeL	2.92	1.01	9.49	14.66
MgK	7.34	5.85	280.53	7.5
AlK	5.31	3.81	229.53	6.91
SiK	15.32	10.56	749.13	5.09
S K	0.06	0.04	2.85	63.63
K K	1.24	0.61	50.31	10.31
CaK	8.14	3.93	280.97	3.42

Figure A-11: EDAX with acetic acid treatment after combination