

THE EFFECTS OF POST FIRE RE-CURING ON MECHANICAL PROPERTIES
AND RECOVERY OF FIBER REINFORCED CONCRETE

by

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ABSTRACT

THE EFFECTS OF POST FIRE RE-CURING ON MECHANICAL PROPERTIES AND RECOVERY OF FIBER REINFORCED CONCRETE

High temperatures or fire may cause significant damage in concrete. Moreover, further deterioration continues at the post heating stage. Although, there are few studies on the post fire rehabilitation of concrete in the literature, most of them focused only on the re-strengthening of concrete. On the other hand, the post fire activities in concrete have a significant impact on both mechanical and microstructural properties of concrete. Therefore, in this study new solution based re-curing techniques were utilized on the concrete specimens at the post heating stage. 7 days of post fire re-curing was applied in order to be more effective, practical and cost effective compared to the longer re-curing periods. At every stage of heating, cooling and re-curing; destructive and non-destructive tests were performed on cubic and prismatic specimens in order to determine the residual mechanical properties and to monitor the extent of recovery. Some of these specimens were also subjected to TGA analyses to better understand the microstructural changes of concrete following heating and the effect of re-curing methods. The results showed further deterioration in air re-cured concrete but recovery in water and solution based re-cured concrete.

ÖZET

YANGIN SONRASI YENİDEN KÜRÜN LİFLİ BETONUN MEKANİK ÖZELLİKLERİ VE İYİLEŞMESİ ÜZERİNE ETKİLERİ

Yüksek sıcaklıklar veya yangın betonda ciddi hasara sebep olabilir ve dahası kötüleşme süreci ısıtma sonrasında da devam edebilmektedir. Literatürde yangın sonrası iyileştirmeye yönelik az sayıda çalışma olmasına rağmen bunların çoğunluğu sadece dayanımın geri kazanımı ile ilgilidir. Öte yandan yangın sonrasında betonda oluşan aktiviteler betonun hem mekanik özelliklerini hem de içyapı özelliklerini ciddi bir şekilde etkileyebilmektedir. Bu sebeple bu çalışmada ısıtma sonrasında beton numunelerine solüsyon bazlı yeni kür yöntemleri uygulanmıştır. Uzun kür sürelerine göre daha etkili, pratik ve ekonomik olması için yangın sonrası kür 7 gün olacak şekilde uygulanmıştır. Kalan mekanik özelliklerin belirlenmesi ve iyileşmenin büyüklüğünün takibi için küp ve prizma numuneleri ısıtmanın, soğumanın ve yeniden kürlemenin her aşamasında tahribatlı ve tahribatsız deneylere tabi tutulmuştur. Ayrıca bu numunelerden bazıları ısıtma sonrasında betonda oluşan değişiklikleri ve yeniden kürlemenin etkilerini daha iyi anlamak için termogravimetri analizlerine de tabi tutulmuştur. Sonuçlar hava kürüne maruz bırakılan numunelerde daha fazla kötüleşme gösterirken su ve solüsyon bazlı küre maruz bırakılan numunelerde iyileşme göstermiştir.

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LIST OF SYMBOLS

C	0.9464 (L3T/bt3), m^{-1} for a prism
$C1, C2, C3$	First, second and third casts respectively
D	Density
L	Length of specimen
M	Mass of specimen, kg
m	Moisture content
m_{cc}	Mass of $CaCO_3$
m_{CH}	Mass of $Ca(OH)_2$
M_{dry}	Mass of dried sample
M_{hum}	Mass of the specimen in the moist state
n	Fundamental transverse frequency, Hz
V_c	Volume of container

LIST OF ACRONYMS/ABBREVIATIONS

ASTM	American Society for Testing and Materials
EN	European Norm
GGBFS	Ground Granulated Blast Furnace Slag
J.A.C	Just After Cooling
NFPA	National Fire Protection Association
OPC	Ordinary Portland Cement
PC	Portland Cement
PC+S	Portland Cement and Ground Granulated Blast Furnace Slag
PP	Polypropylene
W/C	Water to Cement Ratio

1. INTRODUCTION

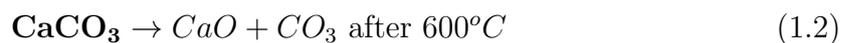
Concrete is the second most consumed material in the world after water and it is the most used construction material. The amount of concrete used in construction is two times more than the amount of all other construction materials combined and this amount is approximately equal to three tons per year utilized for each individual within the world [1]. There are many significant benefits of concrete that make it a very important widely used construction material. Concrete is a cost-effective material that solidifies at room temperature, workable at fresh state and can be easily casted into form-works. Concrete is a very low heat conductor, so it can survive and resist much higher temperatures compared to other building materials like wood and steel. Concrete is used as a fire shield in some extreme environments. Studies in literature examined the effects of elevated temperature and fire exposure on durability of concrete, their outcomes state that concrete has exceptional fire resistance properties; it can maintain its properties for a longer duration when exposed to fire compared to steel and wood and the gases that are emitted from concrete during fire and elevated temperatures are not harmful [2]. On the contrary, concrete samples exposed to fire showed signs of deterioration [3, 4]. Production of concrete needs less energy and the raw materials are widely available, environmentally friendly and can be easily accessed compared to steel. Concrete is a durable construction material, it has a high resistance against normal water and it has more resistance against chemicals compared to steel, this makes concrete a suitable construction material for submerged structures, coastal structures, water linings and pipes, water dams and canals, alongside structures that need to withstand severe chemical and corrosion environments. Concrete properties can be improved and noble properties can be achieved by adding chemical and mineral additives.

Improving the fire performance of concrete can help to limit the damage that happens in concrete at high temperatures. As a result, researchers incorporated a variety of compounds in concrete to improve its fire resistance. A study by Anson *et*

al. [5] looked into the impact of pozzolanic elements such as ground granulated blast furnace slag (GGBFS) on the residual mechanical properties of concrete after fire and found that it had a favorable effect on residual strength and spalling by densifying the microstructure.

Some researchers, on the other hand, focused on the role of fibers in improving concrete's fire resistance. The effect of adding polypropylene (PP) fiber to concrete that had been exposed to 800°C was researched by Quenard *et al.* [6] Outcomes of their research revealed that adding PP fiber decreased the danger of concrete spalling. The melting degree of polymer-based fibers is around 170°C. PP fibers melt at this temperature and after 450°C, they totally vanish, leaving behind microchannel that aid in the outward movement of water vapor and gases from concrete pores [3, 7]. Similarly, Hwang *et al.* [8] validated the beneficial effects of PP fibers.

During high-temperature exposure, significant deteriorations happen in concrete, such as the decrease in mechanical performance of concrete due to changes in its internal structure. Several chemical reactions take place inside concrete during heating, such as



Dehydration begins when temperature reaches 400°C and increases until the calcium silicate hydrate (C-S-H) gels are completely decomposed [9]. CaO and C-S are reactive products and they can react with airborne water molecules and CO₂ after heating. After fire (or exposure to high temperature), if concrete is left without applying any re-curing, it will be air re-cured, during this process, amount of portlandite (Ca(OH)₂) continue to increase on the surface level as it is formed by a reaction between CaO and water particles in air which is an expansive reaction and result in volume increase, this can be one of the main reasons of surface cracks, performance weakening,

post fire degradation and Disintegration of concrete after fire [3, 10-12]. Figure 1.1 Shows disintegration of concrete samples after heating and 7 days after heating [12].

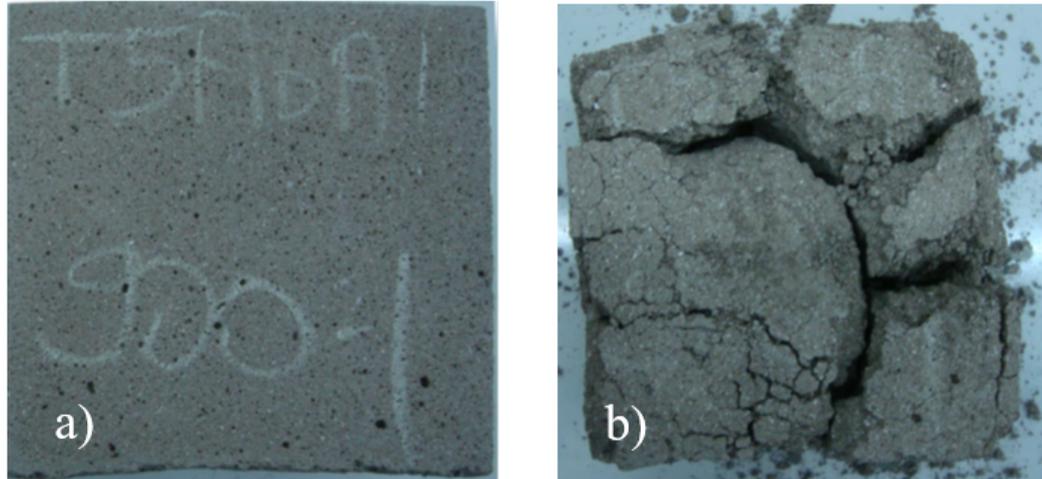


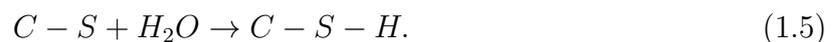
Figure 1.1. Shows disintegration of concrete samples after heating and 7 days after heating [12]. a) after heating. b) 7 days after heating.

Structure fires are continuously increasing, according to a report by Istanbul fire department, residential structure fires increased by 10% and 42% between 2017-2020 and 2020-2021 years, respectively, also, factory fires increased by 72% and 57% during 2017-2020 and 2020-2021 years, respectively [13]. Researches in literature reported continuous post fire degradation of concrete; there are several examples of post fire deterioration and collapse in concrete samples and concrete sections both in laboratory and tragic real life cases. Post fire collapse of concrete samples were reported between after cooling and 7 days after heating [3, 10, 12, 14-19]. There are several cases of post fire collapse of concrete structures and sections after the fire was totally extinguished, seven members of a fire department were killed in Switzerland in 2004 when a concrete building in an underground parking park in which they were present collapsed after they had successfully fought the fire [19, 20]. The risk of post fire collapse of concrete structures may happen at an unexpected time, few moments after fire, during post fire inspections or even several days later, which may put the life of fire fighter and others in danger [19].

Therefore, following a fire, a complex repair operation, such as replacing the damaged layer of concrete, or a re-curing method may be required. Dehydrated internal parts of concrete, however, may have a chance of rehydration when they come into contact with water particles dispersed in concrete after cooling and damaged concrete may restore its strength. Researches [21, 22] reported this occurrence and concluded that if concrete was sufficiently water re-cured or kept in a moist atmosphere, it may restore a significant part of its initial (i.e. pre-fire) strength. Holes and capillaries that are created inside the concrete due to fire will be filled up by products of rehydration-reactions, this will result in decreasing the porosity of concrete which will also lead to strength recovery of concrete. However, rehydration-reactions are critical since products of expanded rehydration, such as CaO expansion, can be detrimental and cause concrete to degenerate as given by



The reaction in is an expansive reaction that may lead to 44% of volume increase. Alternatively, rehydration of C-S may cause recovery and improvement in residual mechanical properties as given by



Therefore, some solutions including HCO_3 or CO_2 ions can enhance the effect of water re-curing by causing carbonation of CaO in concrete. By this way, the detrimental effect of CaO rehydration can be eliminated. It is expected that if concrete is re-cured after fire using $NaHCO_3$ solution, $CaCO_3$ may form and fill the cracks in concrete resulting in increased strength as explained in Figure 1.2 and given by



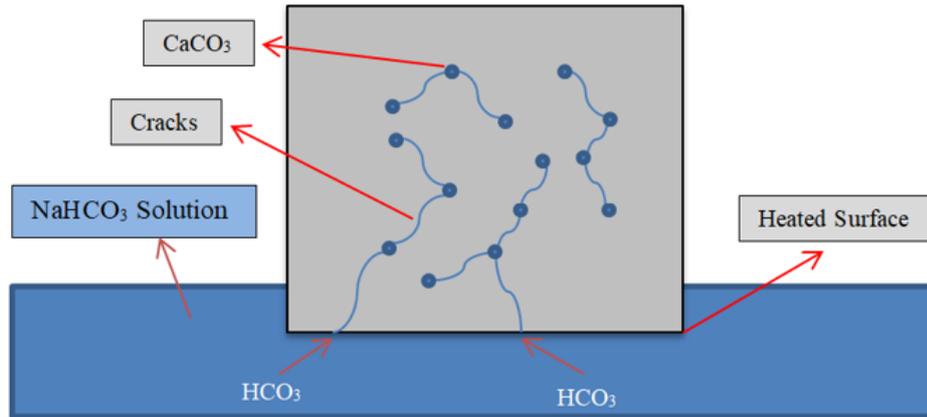


Figure 1.2. NaHCO_3 re-curing.

Using HCl solution can be another option since Cl^- ions diffuse in concrete and form CaCl_2 . CaCl_2 is soluble in water and it can pass into concrete through the re-curing water reaction, as explained in Figure 1.3 and given by

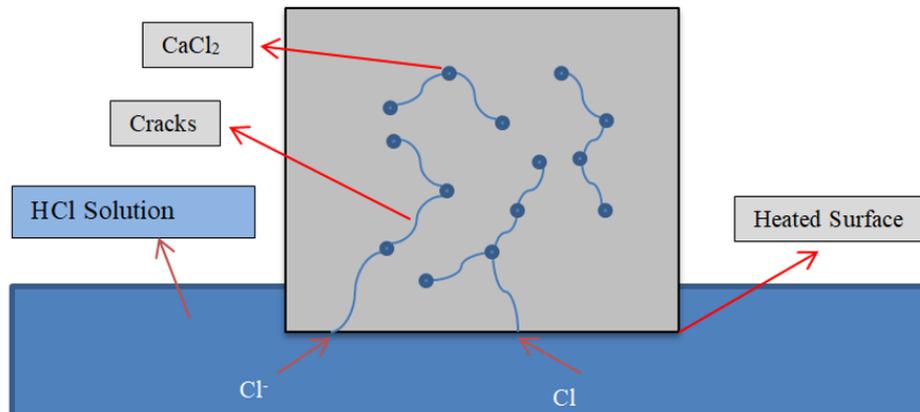


Figure 1.3. HCl re-curing.

These re-curing methods (NaHCO_3 and HCl) are also expected to reduce or eliminate the effect of expansion reaction of CaO . These two hypotheses will be examined in this study.

In the literature, there are few studies on the post fire recovery of concrete. In general, these investigations looked into the re-strengthening of concrete. Nonetheless, post fire internal changes in concrete have a significant impact on the mechanical properties of concrete. Akca and Özyurt [3, 15-18] conducted several researches focusing on the post fire mechanical properties and microstructural changes of concrete. They also tested post fire water re-curing of concrete and they compared this re-curing method to just after cooling (specimens tested immediately after cooling) and air re-curing (specimens were kept in lab environment for a certain time period) methods. The re-curing duration that they used was 27 days. They reported significant increases in strength and modulus of elasticity. However, 27 days is a long period and decreased re-curing times would be very beneficial if made possible. Re-curing concrete after fire using HCl and NaHCO₃, contrarily, can have significant results as it was explained theoretically. Furthermore, choosing a 7 days post fire re-curing duration can also be effective, more practical, more cost effective and takes less time. As a result, an experimental study was prepared to test mentioned hypothesis, following completion of all pre-heating assessments, one side of concrete samples was exposed to the ISO-834 fire scenario to mimic a fire scenario using an electrical furnace. Addition of Ground-granulated blast-furnace slag (GGBS), and using different post fire re-curing methods were selected as test parameters and the impact of these parameters on the mechanical properties and microstructural changes of concrete after fire were studied. Cubic and prism specimens were cast, then, destructive and non-destructive tests were performed on them. These specimens were also subjected to TGA analyses to better understand the microstructural changes of concrete following heating and the effect of re-curing methods.

1.1. Fire

Fires have existed from the beginning of time, caused by natural occurrences. Early human discovered how to manipulate fire and use its advantages. However, disasters may happen due to fires caused by human errors, destroying their habitat and affecting their lives, these reasons made early human to start their efforts in investi-

gating and studying fire in order to understand its behavior better and try to prevent and reduce its damages.

Figure 1.4 [23] shows six classes of fires which are classified based on the source and the main fuel of the fire and five types of extinguishers and their colors and their suitability for extinguishing each class of fire and important comments about each extinguisher.

Type of fire	Extinguisher Colour				
	RED Water	CREAM Foam	BLUE Dry Powder	BLACK CO2	YELLOW Wet Chemical
CLASS A Combustible materials (e.g. paper & wood)	✓	✓	✓	✗	✓
CLASS B Flammable liquids (e.g. paint & petrol)	✗	✓	✓	✓	✗
CLASS C Flammable gases (e.g. butane & methane)	✗	✗	✓	✗	✗
CLASS D Flammable metals (e.g. lithium & potassium)	✗	✗	✓	✗	✗
ELECTRICAL Electrical equipment (e.g. computers & heaters)	✗	✗	✓	✓	✗
CLASS F Deep fat fryers (e.g. chip pans)	✗	✗	✗	✗	✓
Additional Information	Not for use on liquid or electrical fires	Not suited to domestic use	Can be used safely on electrical items up to 1000 volts	Safe on both high and low electrical voltage	For use on extremely high temperatures

Figure 1.4. Classes of Fire [23].

According to the National Fire Protection Association (NFPA), fire can be categorised into five classes based on the type of fuel [24]:

- Combustible materials, like wood, paper and many polymers, are classified as Class A. When they are ignited with an ember, they produce ash. This is the most prevalent type of unintentional fire that occurs in a variety of sectors. Reducing

the temperature of the fuel can help in the extinguishing process. Water and other extinguishers can be used to extinguish this type of fire except CO₂ (i.e. black coloured) extinguishers.

- Fires caused by the ignition of flammable materials containing spectrochemical elements are classified as Class B. Burning materials must be suppressed, this can be achieved by putting a barrier between the fuel and the oxygen source. Foam, Dry powder and CO₂ extinguishers can be used to extinguish a Class B fire. Water and wet chemicals may not be able to put out this type of fire with a high risk of increasing the spread of the fire.
- Class C fuels are those that might be categorized as A or B, excluding stimulated electrical equipment. The foremost frequent extinguishers of this type of fire are carbon dioxide and dry chemical extinguishers. Because water transmits electricity, its use is extremely hazardous.
- Class D metals are burnable metals such as potassium and zirconium. Several of those metals are found in most vehicles. Dry powders are suitable extinguishers to extinguish this type of fire. Water cannot be used as it can be a fuel for this type of fire.
- Fires that are caused by inflamed cooking fats and oils are classified as Class K. Wet chemical (yellow color) are suitable extinguishers for class K fires.

1.2. Fire Tests and Curves

Understanding the behavior of structural fire and construction materials during fire is very important, this can be achieved by designing a fire tests and curves that can reveal the temperature-time curves, response of a material to fire and investigate how a material affects the progression of a fire. There are many different types of fire tests and curves designed by different countries based on international and their national codes, results are used to design fire safety standards [25, 26]. Many researches have been conducted on an international base to establish fire curves that can mimic real structure fire scenario; they are listed below. Even though these fire curves are established based on national and international standards, a study by NIST [27] suggests that these fire

curves are not very accurate in representing a real structure fire and more researches need to be done to improve them. Fire curves are shown in Figure 1.5.

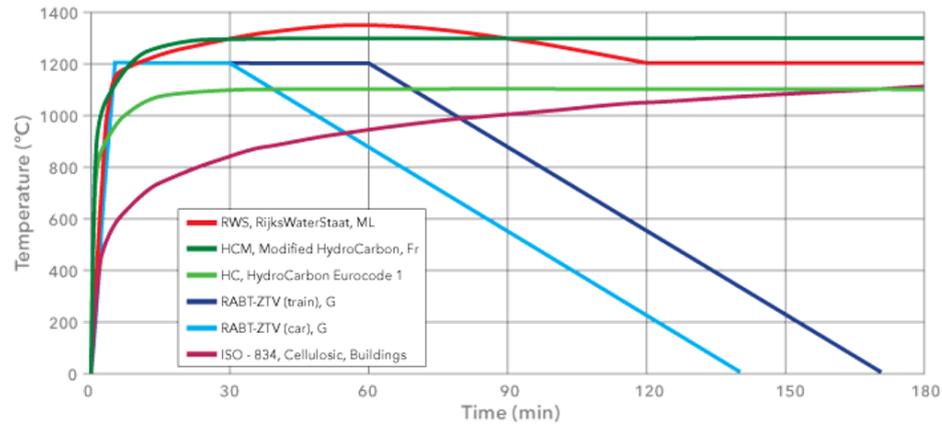


Figure 1.5. Fire Curves [16].

1.2.1. Cellulosic Curve

This fire curve is one of the extensively used fire curves. Cellulosic Curve was established focusing on the behavior of building materials when exposed to fire, thus, this curve better mimics building fire scenario. This fire curve is in compliance with ISO834 standard and it is also recognized by other standards like; DIN4102, BSEN1363-1, AS1530 and BS476:Part20. Temperature progression of this curve is represented in Figure 1.6 [25] and it was calculated by

$$T = 20 + 345 * LOG(8 * t + 1). \quad (1.8)$$

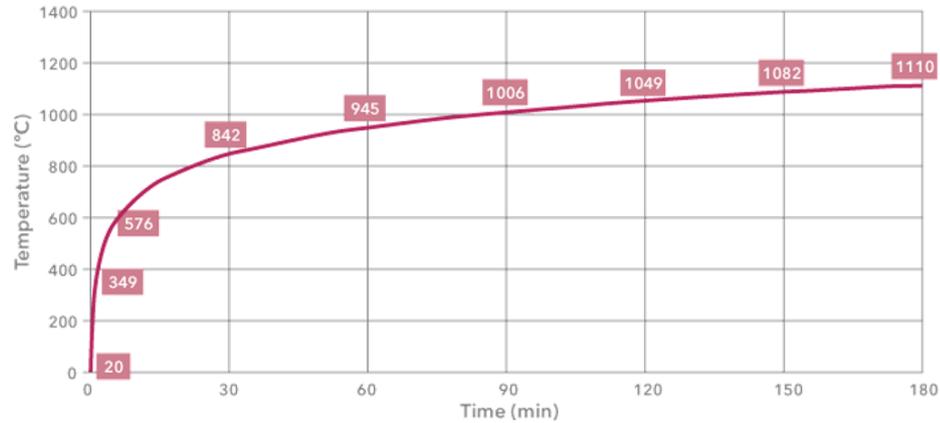


Figure 1.6. Cellulosic Fire Curve [25].

1.2.2. Hydrocarbon Curve

Cellulosic curve couldn't be very accurate in representing the real fire scenario for all materials, as some chemical materials used in petro-chemical sector burn at a much higher rate compared to other materials like wood. Consequently, a new technique of testing especially for materials that are utilized in the petrochemical sector was required, so this curve was created [25]. The temperature progression of this curve can be represented Figure 1.7. A modified version of this curve was developed and the highest temperature of the curve was increased from 1100°C to 1300°C as it can be seen in Figure 1.8 [25]. Temperature progression of this curve is represented by

$$T = 20 + 1080 * (1 - 0,325 * e^{-0.167*t} - 0675 * e^{-2.5*t}) \quad (1.9)$$

$$T = 20 + 1280 * (1 - 0,325 * e^{-0.167*t} - 0675 * e^{-2.5*t}). \quad (1.10)$$

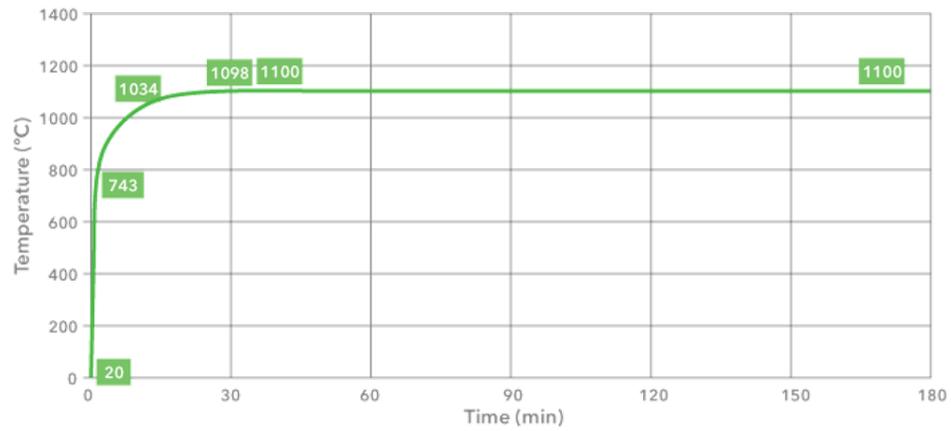


Figure 1.7. Hydrocarbon Curve [25].

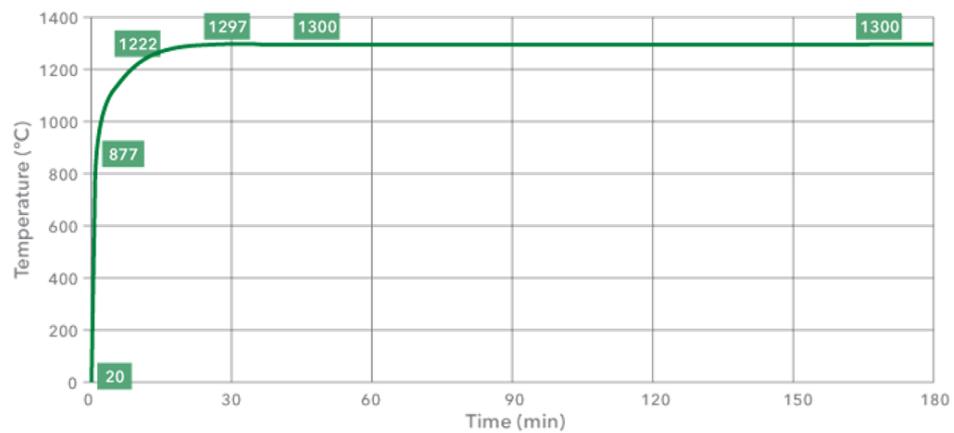


Figure 1.8. Modified Hydrocarbon Curve [25].

1.2.3. RWS Curve

Dutch Ministry of Transportation designed this fire curve; it represents a very severe fire scenario with a 300 MW fire capacity for two hours. This curve was designed based on a large-scale fire; the test took place in a tunnel by TNO, hence this fire curve is more accurate for tunnel fire safety design [25]. Figure 1.9 demonstrates RWS fire curve.

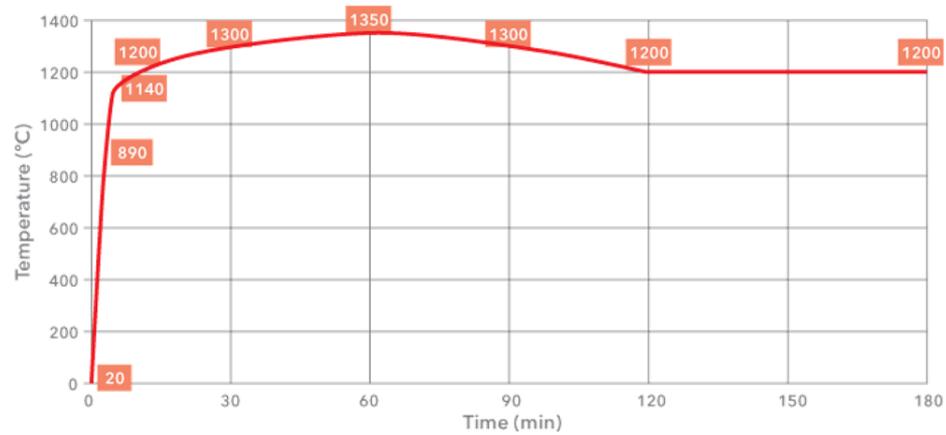


Figure 1.9. RWS Fire Curve [25].

1.2.4. RABT-ZTV Curves

These curves were designed in Germany depending on results of Eureka tests. The RABT-ZTV has two curves to represent car and train fires. What makes these curves different from other curves is that temperature increases in a very fast way and reaches 1200°C in five minutes. Nevertheless, unlike other fire curves, these curves have less exposure time so the fire begin to cool off after 30 minutes in the case of car fire and after one hour in the case of train fire. For both cases, cooling duration is 110 minutes [25]. Figure 1.10 illustrates both RABT-ZTV fire curves.

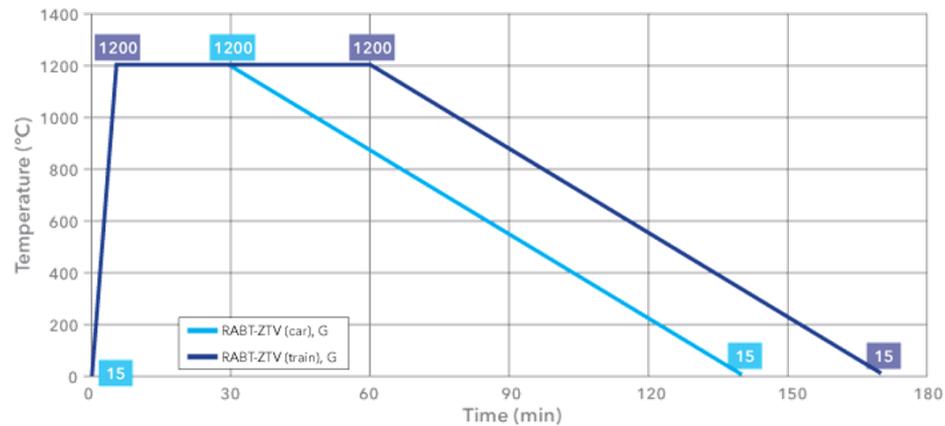


Figure 1.10. RABT-ZTV Fire Curves [25].

1.3. Effects of High Temperature on Concrete

Buildings, atomic reactor plants, airport runways, blast furnaces, industrial structures and missile pads are examples of concrete structures that are subjected to elevated temperatures and fire. Concrete resists moderate temperatures but it may degrade and lose its mechanical properties when subjected to very severe high temperatures and fire [26].

Besides the maximum exposer heat during fire, there are other external elements like initial temperature before heating, duration, the temperature increasing rate and some internal elements like water content, w/c ratio, the age and the kind of concrete and the kind of utilized aggregate, affect the behavior and degradation of concrete during fire. As a result, the findings from the same concrete fire tests performed on similar samples in the literature might be different from each other [2].

1.3.1. Compressive Strength

When concrete is exposed to elevated temperatures, some physical and chemical internal changes occur inside concrete, as shown in Figure 1.11, hydrothermal reac-

tions, releasing free and chemical bounded water, begin when heat reaches 100°C, decomposition of Ca(OH)_2 begins when heat reaches 400°C, CaCO_3 decomposition begins when temperature reaches 600°C and shrinkage of concrete begins, moisture inside concrete totally evaporates at 800°C and concrete starts melting at 1200°C. These internal changes affect the mechanical properties of concrete. Concrete can keep its strength up to 300°C, report by poon *et al.* [22] state that 93% of concrete strength can be recovered for heat exposer under 600°C. However, after 600°C concrete shrinkage begins and mechanical properties of concrete significantly decrease [28]. Different studies in literature state that concrete lose 40 percentage to 60 percentage and 70 percentage to 80 percentage of its mechanical strength when exposed to 600°C and 800°C, respectively [29-31].

Researches in literature state that using mineral admixtures like GGBFS (ground granulated blast furnace slag) and PFA (pulverized fly ash) improve concrete's fire performance and reduce strength loss of concrete post fire. Pool *et al.* [5] studied the effect of adding two mineral admixtures on fire performance of concrete samples which were exposed to 800°C. Table 1.1 shows the outcomes of their research. According to their results, using GGBFS reduced the post fire strength loss by 9%, 22% and 10% on average for samples that were exposed to 400°C, 600°C and 800°C, respectively and using PFA reduced the post fire strength loss by 11%, 11% and 7% on average for samples that were exposed to 400°C, 600°C and 800°C, respectively. A research by Seleem *et al.* [32] also states that using mineral admixtures improve fire performance of concrete and reduce post fire decrease of concrete strength.

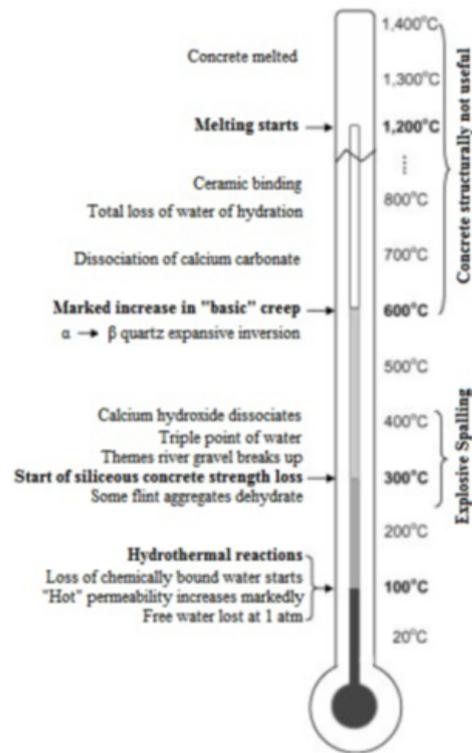


Figure 1.11. Changes inside concrete when exposed to fire [25].

Table 1.1. Reduction in residual compressive strength of normal strength concrete incorporating pozzolanic materials [5].

Concrete Groups	Reduction in Compressive Strength (%)		
	400°C	600°C	800°C
Portland Cement Concrete	26	70	90
Concrete with PFA (30% of cement replacement)	14	63	84
Concrete with PFA (40% of cement replacement)	16	55	82
Concrete with GGBFS (30% of cement replacement)	15	49	79
Concrete with GGBFS (40% of cement replacement)	19	46	80

Researches in literature studied the effect of using fibers on fire performance of concrete, PP (polypropylene) fibers are used as low melting point fibers and their usage was proved to have positive effect on fire performance of concrete as they melt around 175°C and create passages and pores inside concrete that enables water vapors

to escape [3, 33-36], their positive effect on reducing the spalling of concrete during fire and elevated temperatures and a negative effect due to increased porosity have been reported [3, 37, 38].

1.3.2. Modulus of Elasticity

Fire affects the concrete morphology and internal materials that are responsible of providing mechanical performance and protecting the reinforcement bars [39]. When concrete is exposed to fire, cracks form inside and evaporated water forms an internal pressure, thus modulus of elasticity is also affected during fire and post fire. Neville [2] state that when concrete is exposed to heat, reduction in modulus of elasticity increases with temperature rise, this reduction reaches 50% when exposed heat reaches 500°C and mechanical performance is greatly affected by this reduction. Researches in literature reported the positive effect of using GGBFS in concrete on the modulus of elasticity during and post fire, 10 percentage and 30 percentage usage of GGBFS as a binding material were tested, as it can be seen in Table 1.2, using GGBFS increased the residual modulus of elasticity by 2%, 3.5% and 0.5% when concrete was exposed to 300°C, 500°C and 700°C, respectively [40].

Table 1.2. Residual modulus of elasticity of concrete incorporating GGBFS [32].

Concrete Group	Residual Modulus of Elasticity (%)		
	300°C	500°C	700°C
Portland cement concrete	45	70	93
Concrete with GGBFS (10% of cement replacement)	46	72	94
Concrete with GGBFS (30% of cement replacement)	48	75	93

1.3.3. Duration of Heat Exposure

Generally, concrete has very low heat conduction, so it can survive and resist much higher temperatures compared to other building materials like wood and steel, therefore, concrete is used as a fire shield in some extreme environments. Studies in literature examined the effects of elevated temperature and fire exposure on durability of concrete, outcomes state that concrete has exceptional fire resistance properties; it can maintain its properties for a longer duration when exposed to fire compared to steel and wood. However, when concrete is exposed to fire or very high temperatures for a long time, mechanical properties of concrete decrease and post fire degradation will be possible. The effect of high temperature exposing period on mortar strength was studied by Cülfik and Özturan [10], several mortar samples were exposed to three different temperatures and two exposure durations as it can be seen in Table 1.3, outcomes of their study show that samples that were heated for one hour received less damage and their residual mechanical strength were higher than samples which received ten hours 900°C heat exposure.

Table 1.3. Residual mechanical properties after extended heat exposure [33].

Maximum Temperature (C)	Exposure duration (h)	Compressive Strength (%)	Flexural strength (%)	Modulus of Elasticity (%)
300	1	87	85	67
	10	82	68	65
600	1	49	22	16
	10	40	14	14
900	1	15	9	-
	10	12	7	-

1.3.4. W/C Ratio and Moisture Content

Low w/c ratio has positive effect on strength and mechanical properties of concrete, but it may have negative effect on the fire performance and post fire residual

mechanical properties of concrete, as concretes with low w/c are denser and have less internal pores and voids, when exposed to fire or elevated temperature, moisture inside concrete evaporates and because the concrete has low porosity, the evaporated moisture doesn't find a way to escape the internal structure thus a significantly high pressure accumulates inside concrete which may lead to increased internal cracks and risk of spalling. Chan *et al.* [41] examined the effect of low w/c ratio on the fire performance of concrete by heating a normal strength concrete and a high strength concrete up to 800°C, outcomes of their study show that post fire residual compressive strength of normal strength samples (i.e. normal w/c ratio) was 45 percent while post fire residual compressive strength of high strength samples (i.e. low w/c ratio) was 28 percent of their original strength.

High moisture content also increases the risk of spalling. According to previous studies, moisture content has a direct relation with spalling, concrete with high moisture content has high risk of spalling, concretes do not spall if their moisture content by weight is 3% or less and concretes with higher moisture content than 3% have risk of explosive spalling [34]. A study by Shorter and Harmaty also state that dry materials do not spall even if exposed to high temperature [42]. Mayer-Otters discuss that at elevated temperatures; the steam inside the pores of concretes with moisture content higher than 3% may cause a tensile strength as high as the tensile strength of the concrete which may lead to explosive spalling [43].

1.3.5. Mass Changes

Concrete samples lose a significant amount of their mass after being exposed to elevated temperature. Mass loss happens during the process of heating due to evaporation of free water at the beginning of the heating process, then at higher temperatures, chemically bonded water evaporates, then decarbonation of carbonates begin at temperatures around 600°C which lead to release of Carbon dioxide, mass loss is continued until the end of the heating process (1000°C) [3, 11, 44].

1.4. Re-Curing Concrete After Fire

Re-curing in water and other autogenic self-healing processes have been shown to partially recover concrete's strength. The level of recovery is determined by a number of factors, including concrete type, maximum temperature exposed, rate of heating and type of after fire re-curing. Self-repair technology can be characterized as autogenous or autonomous, according to Lv and Chen's research [45]. When concrete is self-healed, it's possible that the wound will heal itself, which is referred to as autogenous healing. Water re-curing, for example, is proven to have the ability to recover mechanical properties of concrete after fire. Schlangen *et al.* [46] investigated the autogenous self-healing and came to the conclusion that autogenous self-healing is induced by additional hydration of unhydrated cement clinker. The primary principles of autogenous self-healing are: hydrating unhydrated cement, recrystallizing portlandite leached from the bulk paste and calcite production [47]. Self-healing skills can be achieved by the release of encapsulated repair-admixture owing to crack from the outset of damage for autonomous healing.

Researchers in the literature, [15-18] who noticed that some samples which were exposed to elevated temperature and left in the open air to be air re-cured were completely demolished after few days. They also compared air and water recurring methods on PP fiber reinforced PC and PC+S concrete for a duration of 27 days and the results indicated that water re-curing method was an effective re-curing method that helps the concrete in regaining and improving post fire mechanical properties. Other researches [19, 27] also state post fire collapse of concrete structures which were left in open air few days after they were exposed to fire.

Studies in literature [48, 49] state that carbonation has a significant positive affect on the compressive strength of concrete because carbonation increase calcium carbonate and decrease calcium hydroxide inside concrete. Therefore, post fire re-curing concrete using HCl and NaHCO_3 might have a positive effect on recovering mechanical properties of concrete.

2. EXPERIMENTAL STUDY

For the purpose of studying and investigating the behavior of concrete after fire and comparing different post fire re-curing technics, 2 groups of concrete were produced and 4 different post fire re-curing methods were applied. Each group of concrete contain both cubic and prism samples, chemical admixture and polypropylene fibers were used in all samples, ground granulated blast furnace slag (GGBFS) was used in one group of samples in order to examine their effect.

Both destructive and non-destructive tests were conducted to examine their properties in each stage; before heating, post heating and after applying each re-curing method.

2.1. Materials

2.1.1. Cement

In this study, Ordinary Portland Cement (OPC) CEM I 42.5 R cement was used in all samples. Source of this OPC is AKCANS A cement factory. Chemical Composition is given in Table 2.1. Mineralogical Composition is given in Table 2.2, and Table 2.3 shows mechanical properties. These properties are taken from report No: BÇM2015/21 provided by the producer factory.

Table 2.1. Chemical Composition of Ordinary Portland cement.

Chemical Composition			
Composition	(%)	Composition	(%)
SiO ₂	19.63	CaO	63.67
Insoluble residue	0.28	MgO	1.25
Al ₂ O ₃	5.58	LSF	0.96
Fe ₂ O ₃	3.32	SO ₃	3.23
Loss in ignition	2.03	Free CaO	2
Cl-	0.04	Residue on 45 um sieve	4.5
Na ₂ O	0.21	Residue on 90 um sieve	0
Specific gravity (kg/m ₃)	3140	Residue on 200 um sieve	0

Table 2.2. Mineralogical Composition of Ordinary Portland Cement.

Mineralogical Composition	
C3S	50.36
C3A	9.18
C2S	18.37
C4AF	10.1

Table 2.3. Mechanical Properties of Ordinary Portland Cement.

Mechanical Properties			
Mechanical Characteristic	Day	Standards	Test results
Early Strength	2	20.0 MPa	28.3 MPa
Early Strength	7	-	42.1 MPa
Standard Strength	28	42.5 MPa	54.8 MPa
		62.5 MPa	

2.1.2. Ground Granulated Blast Furnace Slag (GGBFS)

Table 2.4 and Table 2.5 presents physical properties and chemical properties of (GGBFS). These properties are provided by the producer factory.

Table 2.4. Physical properties of ground granulated blast furnace slag.

Physical Property	Test Result
Density	2920 (kg/m ³)
Pozzolanic Activity Index 7 day	52.3 (%)
Pozzolanic Activity Index 28 day	74.4 (%)
Residue on 45_μ sieve	1.1 (%)

Table 2.5. Chemical properties of GGBFS.

Composition	(%)	Composition	(%)
SiO ₂	40.95	Na ₂ O	0.56
Al ₂ O ₃	12.1	K ₂ O	0.36
Fe ₂ O ₃	1.28	Cl-	0.02
CaO	36.63	MgO	5.48
Loss on ignition	0.11	SO ₃	0.16

2.1.3. Aggregates

In the concrete mixes, siliceous crushed stone is used for coarse aggregates and siliceous river sand is used as fine aggregates, their specific gravities are 2.70 and 2.65, respectively.

2.1.4. Fibers

Multi Filament polypropylene (PP) fibers were used in this study. Properties of used fiber are given in Table 2.6.

Table 2.6. PP Fiber Properties.

Properties	Unit	PP fiber
Diameter	μm	32
Length	Mm	12
Modulus of elasticity	GPa	3.5
Tensile strenght	MPa	250
Aspect ratio	/	375
Specic gravity	/	0.91
Melting Point	C ^o	165

2.1.5. Admixture

Chemical admixture; Rheobuild 1000 superplasticizer was used in both concrete groups. Rheobuild 1000 is a water reducing, strength enhancing high range superplasticizer that contains sulphonated polymer. Table 2.1 presents properties of this superplasticizer.

Table 2.7. Superplasticizer properties..

Density (g/cm)	1.2
pH	6-10
Color	dark brown

2.1.6. Re-curing Materials

NaHCO₃ and HCL were used as re-curing materials, they were purchased from “Bereket Kimya”, and Table 2.1 presents their properties.

Table 2.8. NaHCO₃ Properties.

NaHCO ₃	
Molecular weight (g/mol)	84
Density (g/cm)	2.2
Purity	99%
Melting Point	270°C
Boiling Point	851°C

Table 2.9. HCl Properties.

HCl	
Molecular weight (g/mol)	36.5
Density (g/cm ³)	1.2
Purity	30-33%
Melting Point	-35°C
Boiling Point	57°C

For NaHCO₃, 1.2 kg of sodium bicarbonate powder was added to 15 liters of water, magnetic fish was used in order to make sure that the sodium bicarbonate powder is well solved in water.

For HCl re-curing method, re-curing liquid was prepared by adding 1 liter of HCl to 14 liters of water, then the liquid was mixed well and placed into a plastic container, precautions were taken and laboratory equipment (glasses, mask, gloves, etc.) were

worn while handling hydrochloric acid in order to prevent any hazard since it is a strong hazardous acid.

2.2. Mix Properties and Casting

2.2.1. Mix Properties

Two concrete groups were prepared, Ordinary Portland Cement CEM I 42.5 R, river sand, water, siliceous gravel, fiber and superplasticizer were used in all samples. Water to cementitious ratio was 0.45 for both groups. Ground Granulated Blast Furnace Slag (GGBFS) was used in one group as a variable parameter to investigate its influence as a cement replacement material with a ratio of 40%, previous studies found this GGBFS cement replacement ratio to be optimum [5, 50]. GGBFS cement equivalency factor is given to be 0.8. TS EN 206-1 and TS 13515 standards were used to determine the water contents. Rheobuild 1000 superplasticizer was used in both concrete groups as a chemical admixture. Multi Filament polypropylene (PP) fibers were used in both concrete groups. Mix properties of both concrete groups are presented in tables 2.10 and 2.11. “PC” stands for the group that was prepared using ordinary Portland cement as the only cementitious material, while “PC+S” stands for the group that was prepared using both ordinary Portland cement and GGBFS.

Table 2.10. Mix properties of 1st group (PC).

1st group (PC)	
Materials	Weight (kg)
OPC	450
Water	202.5
Aggregate No1	484
Aggregate No2	484
Crushed Sand	565
River Sand	225
Super Plasticizer	6.3
PP fiber	1.8

Table 2.11. Mix properties of 2nd group (PC+S).

2nd group (PC+S)	
Materials	Weight (kg)
OPC	270
GGBFS	108
Water	186
Aggregate No1	493
Aggregate No2	493
Crushed Sand	574
River Sand	229
Super Plasticizer	7.8
PP fiber	1.8

2.2.2. Casting Procedure

Casting and curing were done in Boğaziçi University Construction Materials Laboratory, a 60 dm³ pan mixer was used and the mixing process was 5 minutes long;

- (i) Cement (OPC), fine and coarse aggregates, PP fiber and GGBFS (for 2nd Group) were dry mixed for 2 minutes,
- (ii) Then superplasticizer and water were added to the mix in 1 minute,
- (iii) All materials were mixed for another 2 minutes,
- (iv) Slump and density of the fresh state concrete was measured following ASTM C138 [51].
- (v) Then concrete was casted into prism and cubic molds in 3 stages; vibration was applied to the molds in each stage, specimens were left in laboratory environment for 24 hours.

After 24 hours, molds were removed, specimens were labeled and they were placed in a water curing tank with 20 ± 2 water temperature for 28 days in accordance with EN 12390-2 standard.

2.2.3. Specimens

In total, 104 samples were cast, prism and cubic samples were cast for each concrete group, after 28 days of curing and samples were left in the laboratory environment for 6 months. Table 2.122 shows the number and types of the specimens, “PC” represents the concrete mix cast with OPC as the only binding material and “PC+S” represents the concrete mix cast using both OPC and (GGBFS).

Table 2.12. Concrete specimens.

Mixes	Dimensions	Type	Quantity
PC	15*15*15	Cubic	26
	7.5*10*40	Prism	26
PC+S	15*15*15	Cubic	26
	7.5*10*40	Prism	26

3. EXPERIMENTAL METHODS

3.1. Slump-test

Slump test was conducted on fresh concretes of both concrete groups in accordance with EN 12350-2 standard “Testing fresh concrete. Slump-test”.

3.2. Density Measurement

Wet density of fresh concretes of both concrete groups were measured in accordance with ASTM C138 “Standard Test Method for Density (Unit Weight), Yield and Air Content (Gravimetric) of Concrete” [51], a cylindrical container was used, mass of the empty container was recorded, then the container was filled with fresh concrete in 3 steps with tamping, after that mass of the container was recorded, then the density of fresh concrete was measured using the mass and the volume of the container and it was calculated by

$$D = \frac{M_{CC} - M_C}{V_C}. \quad (3.1)$$

In Equation (3.1);

- D stands for density.
- M_{cc} stands for mass of full container.
- M_{ec} stands for mass of empty container.
- V_c stands for volume of container.

3.3. Measuring Moisture Content

According to previous studies, moisture content has a direct relation with spalling, concrete with high moisture content have high risk of spalling, concretes do not spall

if their moisture content by weight is 3% or less and concretes with higher moisture content than 3% have risk of explosive spalling [34]. A study by Shorter and Harmaty also state that dry materials do not spall even if exposed to high temperature [42]. Mayer-Otters discuss that at elevated temperatures; the steam inside the pores of concretes with moisture content higher than 3% may cause a tensile strength as high as the tensile strength of the concrete which may lead to explosive spalling [43]. Before exposing the samples to elevated temperature, the moisture content of samples from both concrete groups were measured in accordance with BS1353 standard [52], mass of the moist state of the samples were recorded, then they were placed in a drying oven (as it can be seen in Figure 3.1), temperature of the drying oven was put to 100 Co, the mass of the samples were measured every 24 hours until the mass change between two recorded data decreased to less than 0.2%, afterwards the change in the mass was considered to be constant. Moisture content was calculated using

$$m = \frac{M_{hum} - M_{dry}}{M_{dry}}.100. \quad (3.2)$$

In Equation (3.2);

- m stands for moisture content.
- M_h stands for mass of moist samples.
- M_d stands for mass of dried samples.



Figure 3.1. Drying Oven.

3.4. Non-Destructive Test: Resonance Frequency

In accordance with “ASTM C215 - 14” [53] Transverse resonance frequency of the prism specimens were measured before heating the specimens, after heating them and after re-curing them. In the was used to calculate the dynamic Young’s modulus of elasticity. Figure 3.2 shows the setup of the resonance frequency test, the pickup and the driver locations. Dynamic modulus of elasticity was calculated using

$$\text{Dynamic } E = CMn^2 \quad (3.3)$$

In Equation (3.3)

- Dynamic E stands for dynamic modulus of elasticity
- C is a constant which is = 1.6067 (L3T/d4), m-1 for a cylinder, or = 0.9464 (L3T/bt3), m-1 for a prism
- M stands for mass of sample in kg
- n stands for fundamental transverse frequency in Hz.

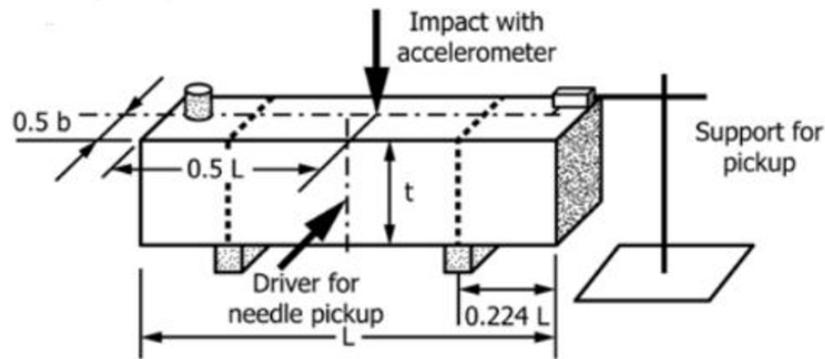


Figure 3.2. Transverse resonance frequency: Driver and Needle Pickup Locations [53].

3.5. Heating

Both cubic and prism specimens were heated using an electrical furnace that has a 1250°C operational capacity. All specimens were heated to 1000°C and kept in this temperature for 60 minutes, in order to achieve a heating rate close to the ISO-834 curve, maximum heating rate capacity of the furnace was used which is $20^{\circ}\text{C}/\text{min}$, temperature of the furnace reached 1000°C in almost 115 minutes, the heating rate of the furnace was decreasing with time until it reached 5°C per minute, this happened due to the limited heating capacity of the furnace. So the total heating time was 175 minutes. After 175 minutes, the furnace was turned off and the hot specimens were kept inside the furnace to cool down until the temperature of the furnace decreased to around 150°C , because opening the furnace at high temperature is dangerous and also it may result damage to the furnace.

For the purpose of monitoring internal heat of the furnace, K-Type thermocouples were placed in the center of the specimens. Thermocouples wires can resist very high temperature so they can be used multiple times. One-face heat exposure was applied, so specimens were covered with aerated concrete blocks and only one side of the specimens were exposed to heat. Specimens were placed inside a cage and the cage was placed at the center of the furnace, the cage was used in order to save the furnace from

unexpected spalling of the specimens during the heating process, 4 cubic specimens and 6 prism specimens were heated together in each heating cycle as it can be seen in Figure 3.3. Heating scenario can be seen in Figure 3.4.



Figure 3.3. Position of the specimens and heat insulations inside the furnace.

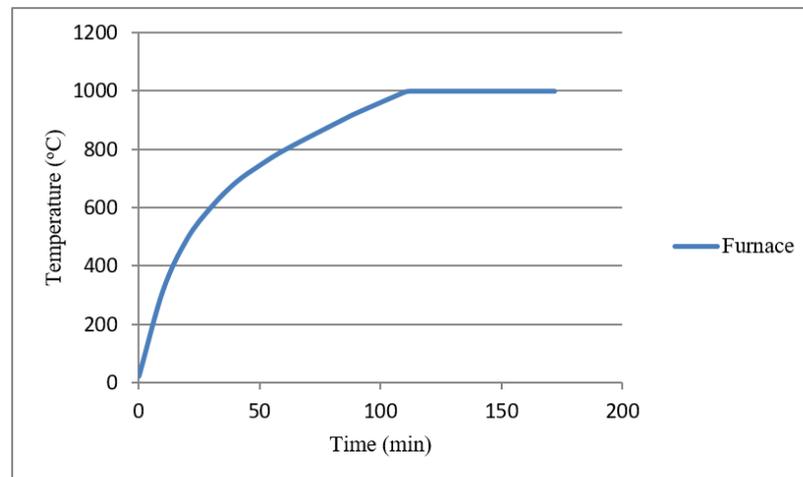


Figure 3.4. Heating Scenario.

3.6. Mass Change Monitoring

Mass of all specimens were measured before heating and samples were left to cool down after heating until they reached room temperature, then their masses were measured and they were also weighed after re-curing.

3.7. Re-curing Procedure

Four types of re-curing were used; water, HCl, air and NaHCO₃ re-curing. After heating, samples were left inside the furnace until the temperature of the furnace decreased to 200°C, then the furnace was opened so that the temperature of the samples decrease to room temperature, air re-cured samples were left in the laboratory , temperature of the laboratory was 20±3°C temperature and 65±12% humidity. Samples that were selected to be water, HCl and NaHCO₃ re-cured were placed in re-curing containers (Figure 3.5) and only their heated face was subjected to re-curing, the containers were air sealed (Figure 3.5 b and c) in order to not let the air in the laboratory environment affect the re-curing process, tap water was used for water re-curing method and also for preparing HCL and Sodium Bicarbonate re-curing liquids, their preparations were mentioned in Section 2.1.6.



Figure 3.5. a) Re-curing container, b) Sealed re-curing container, c) HCl re-curing container.

3.8. PH and Liquid Level Measurement

PH and liquid level of the water, HCL and NaHCO_3 containers was measured before and after each re-curing. This was done to check if samples were absorbing similar amount of water and re-curing liquids and if there is any external factor that may affect the reactions and water absorption rate during the re-curing process. Figure 3.6 shows AD11 pH Meter which was used to measure pH of the curing liquids.



Figure 3.6. AD11 PH Meter.

3.9. Modulus of Elasticity and Compressive Strength Measurement

Fire affects the concrete morphology and internal structure that are responsible of providing mechanical performance and protecting the reinforcement bars [39]. Mechanical strength of samples from each concrete group was measured afore heating, just-after -cooling (J.A.C), and after applying each re-curing method. Results used to assess the influence of each re-curing method on the mechanical strength of samples of both concrete groups. Compressive strength of cubic samples were measured using MTS - 500 kN Servo-Hydraulic Testing Machine (Figure 3.7) and UTEST Automatic Compression Testing Machine with a max loading capacity of 3000 kN (Figure 3.8), modulus of elasticity and length changes of the samples were measured using a compressometer frame with 2 LVDTs as shown in Figure 3.9. One cubic sample from each testing group was tested with the UTEST Compression Testing Machine and the ultimate strength of the sample was recorded.

Compression test of the rest of the cubic samples from the same group started by placing the samples inside the compressometer frame and the MTS testing machine was used, samples were loaded until the loading reached 40% of the previously measured ultimate strength of the concrete samples, then the frame was removed and the rest of the test continued with the UTEST compression testing machine until samples failed.

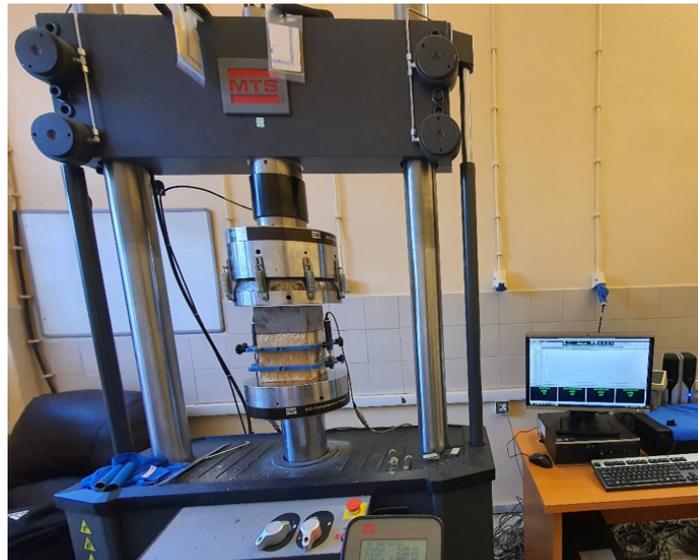


Figure 3.7. MTS Hydraulic Testing Machine.



Figure 3.8. UTEST Automatic Compression Testing Machine.



Figure 3.9. Compressometer frame.

3.10. Thermogravimetric Analysis (TGA)

After measuring compressive strength, TGA Samples from heated surface and core center of cubic samples were collected from each concrete group afore heating, post heating and after each re-curing method, each collected sample was grinded using a ceramic bowl and pestle, powder was produced and 15 mg of each sample's powder was placed in air insulated plastic bags, then they were taken to Yıldız Technical University Laboratory for Thermogravimetric analyses (TGA), "SII Nanotechnology - SII6000 Exstar TG/DTA 6300" thermogravimetric analyzer was used to conduct the test, samples were heated up to 1000°C at a 10°C/min heating rate. A nitrogen atmosphere was maintained by the thermogravimetric analyzer with a 60 mL/min purge rate.

4. RESULTS AND DISCUSSIONS

4.1. Slump Test Results

Workability of the fresh concrete of all concrete casts was measured with the help of slump test which was carried out in accordance with EN 12350-2 standard “Testing fresh concrete. Slump-test”. Table 4.1 shows results of the slump test.

Table 4.1. Slump test results.

# cast	mix	Slump (cm)
1 st	PC	18
	PC+S	13.5
2 nd	PC	18.5
	PC+S	13
3 rd	PC	15
	PC+S	13
4 th	PC	17
	PC+S	14

As it can be seen in the 4.1 table, PC concrete group had an average slump of 17 cm and PC+S concrete group had an average slump of 13.3 cm. These results show that using Ground Granulated Blast Furnace Slag (GGBFS) as a cementitious binding material and a partial substitute for OPC (Ordinary Portland Cement) resulted in decreasing slump of the fresh concrete from S4 workability class to S3, as it was expected.

4.2. Density Measurement Results

Wet density of concrete groups was measured in accordance with ASTM C138 “Standard Test Method for Density (Unit Weight), Yield and Air Content (Gravimet-

ric) of Concrete” [51], procedure was explained in Section 3.2. Table 4.2 shows the wet density of all concrete casts.

Table 4.2. Wet density of concrete groups.

#Cast	mix	Density (kg/dm ³)
1 st	PC	2.34
	PC+S	2.39
2 nd	PC	2.32
	PC+S	2.42
3 rd	PC	2.37
	PC+S	2.41
4 th	PC	2.32
	PC+S	2.42
PC mix average		2.34
PC+S mix average		2.41
Overall average		2.37

4.3. Moisture Content Measurement Results

Moisture content of cubic and prism samples of each concrete group from each cast was measured before exposing them to elevated temperature in accordance with BS1353 [52], details of the procedures were given in Section 3.3. In order to avoid severe spalling and damage while exposing the samples to elevated temperature, less than 3-4% moisture content is desired. As it can be seen in Table 4.3, moisture content of most of the samples were more than 3% and samples from C1 PC and C2 PC had 4.5% and 4.8% moisture content respectively. This high moisture content increases the risk of spalling when exposed to elevated temperature, so it was decided to oven dry all samples before exposing them to elevated temperature in accordance with “BS 1353”

standards [52], all the samples were oven dried until the moisture difference decreased to 0.2% or less within 24 hours.

Table 4.3. Moisture contents before oven drying the samples.

Series	Moisture content %
C1 PC	4.5
C1 PC+S	3
C2 PC	4.8
C2 PC+S	3
C3 PC	3.6
C3 PC+S	3.3

4.4. Non-destructive test: Resonance Frequency Results

Transverse resonance frequency of the prism specimens were measured before heating the specimens, after heating them and after re-curing them. Their dynamic Young's modulus of elasticity was calculated in accordance with "ASTM C215-14" [53] Standard as it was explained in Section 3.4.

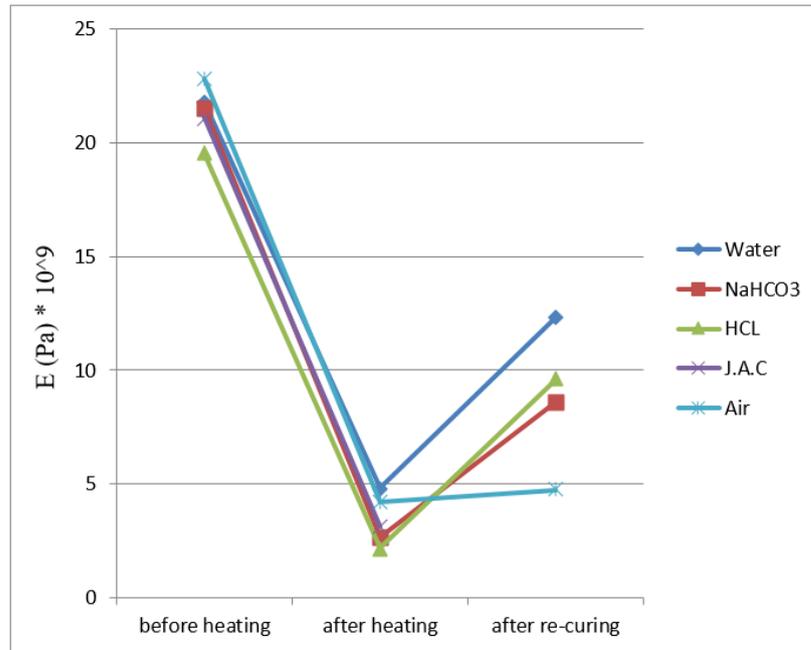


Figure 4.1. Dynamic Young's modulus of elasticity of PC samples.

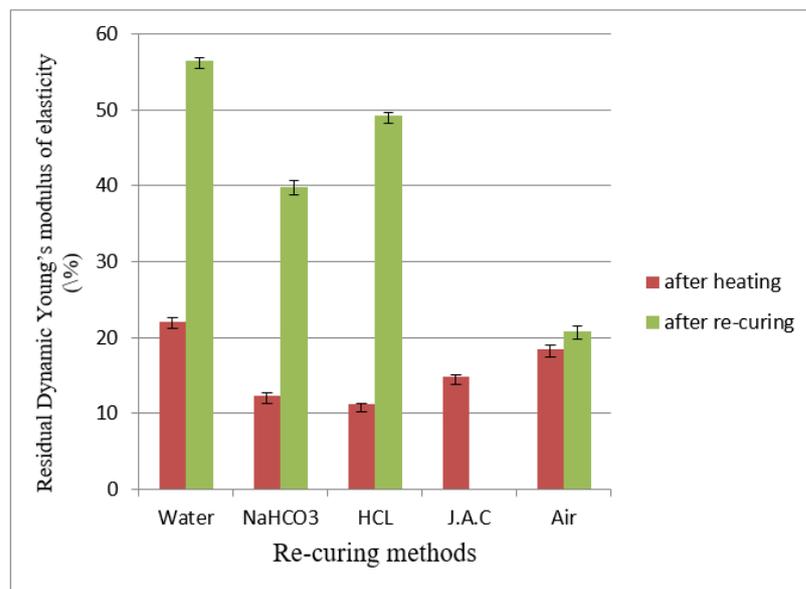


Figure 4.2. Residual Dynamic Young's modulus of elasticity of PC samples.

Table 4.4. Residual Dynamic Young's modulus of elasticity of PC samples.

Residual Dynamic Young's modulus of elasticity				
PC	After heating		After re-curing	
	Average (%)	Standard deviation	Average (%)	Standard deviation
Water	22.1	0.5	56.5	0.3
NaHCO ₃	12.3	0.4	40	0.8
HCL	11.1	0.1	49.2	0.4
J.A.C	14.8	0.2	-	-
Air	18.4	0.5	20.8	0.6

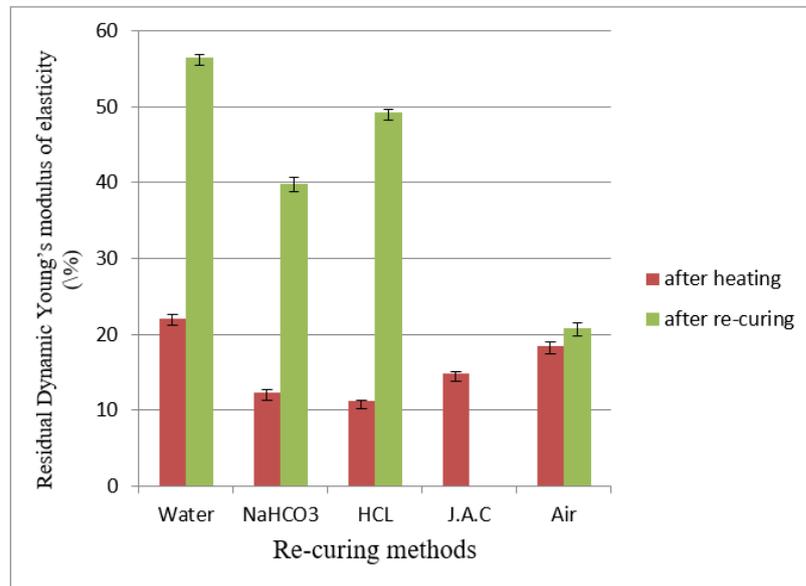


Figure 4.3. Dynamic Young's modulus of elasticity of PC+S samples.

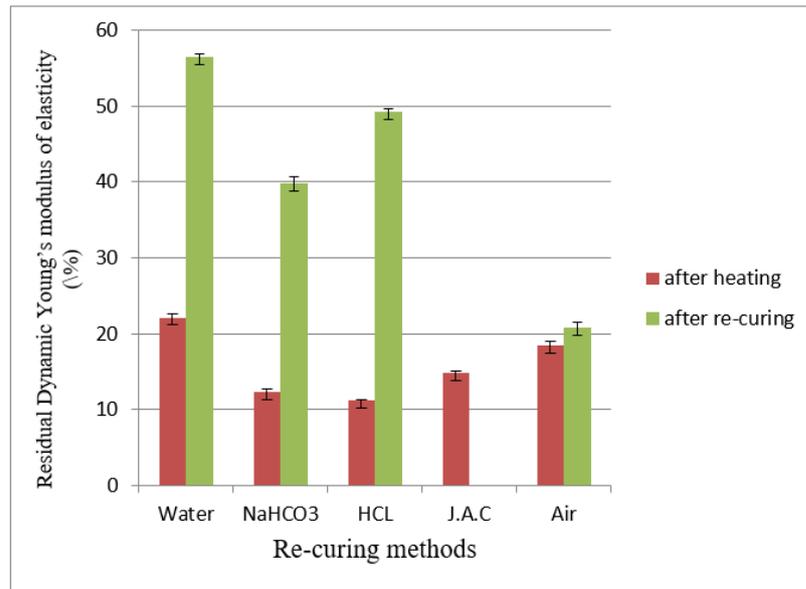


Figure 4.4. Residual Dynamic Young's modulus of elasticity of PC+S samples.

Table 4.5. Residual Dynamic Young's modulus of elasticity of PC+S samples.

Residual Dynamic Young's modulus of elasticity				
PC	After heating		After re-curing	
	Average (%)	Standard deviation	Average (%)	Standard deviation
Water	14.7	0.6	39.3	0.3
NaHCO ₃	16.5	0.3	47.2	0.4
HCL	12.8	0.2	39	0.8
J.A.C	20.4	0.3		
Air	15	0.8	14	0.7

As it can be seen from the results, samples from both concrete groups received a severe damage from the heating process, residual dynamic Young's modulus of elasticity of samples from PC group after heating had an average of 15.7%, and residual dynamic Young's modulus of elasticity of samples from PC+S group after heating had an average of 15.9%.

Table 4.4 and Table 4.5 show that, using water re-curing method for PC samples could recover their mechanical properties, as their residual dynamic Young's modulus of elasticity was 56.5%, which is the highest percentage among all re-cured samples of both concrete groups. Researches in literature [15-18] which were conducted on re-curing concrete after exposure to elevated temperature using different method state that water re-curing method is a very effective re-curing method that helps the concrete in regaining and improving post fire mechanical properties. However, dynamic Young's modulus of elasticity value was lower for the samples of PC+S group that received water re-curing; it was 39.3% of the original value before heating, which means that water re-curing method was more effective in recovering dynamic Young's modulus of elasticity of PC samples.

Second best result was from HCl re-curing method of the PC specimens, residual dynamic Young's modulus of elasticity of PC samples re-cured using HCl method was 49%. Meanwhile, residual dynamic Young's modulus of elasticity of HCl re-cured PC+S samples was 39%, which is lower compare to HCl re-cured PC samples, which means that HCl re-curing method was more effective in recovering dynamic Young's modulus of elasticity of PC samples.

On the other hand, residual dynamic Young's modulus of elasticity of NaHCO_3 re-cured PC samples was 40%, while residual dynamic Young's modulus of elasticity of NaHCO_3 re-cured PC+S samples was 47%, which means that NaHCO_3 re-curing method is more effective in recovering dynamic Young's modulus of elasticity of PC+S samples.

Furthermore, results show that residual dynamic Young's modulus of elasticity of air re-cured PC samples was 20.8%, which is 48% to 63% lower than residual dynamic Young's modulus of elasticity of PC samples that were re-cured using water, NaHCO_3 or HCl re-curing methods. Also, residual dynamic Young's modulus of elasticity of air re-cured PC+S samples was 14%, which is lower than the after heating value, these results support results of other tests of this study and researches in literature who

report that mechanical performance of air re-cured samples continue to decrease after heating.[3, 10, 12, 15-19]. This result also support the suggestion that was mentioned in this study, which state that, when concrete is exposed to elevated temperatures (i.e. Fire), it needs to be re-cured using an effective repairing or re-curing method, otherwise, if concrete is left in open air without applying any other effective re-curing method, air may impose negative effect on the mechanical properties of concrete as it was also mentioned by other researchers in the literature, [15-18] who noticed that samples which were exposed to elevated temperature and left in the open air were completely demolished after few days , other researches [19, 27] also state post fire collapse of concrete structures which were left in open air few days after they were exposed to fire.

4.5. Mass Change Monitoring Results

Mass of all specimens was measured afore heating, post heating and after applying each re-curing.

Table 4.6. Residual Mass by % for PC concrete group.

Residual Mass %			
PC	After Heating %	After Re-curing %	Recovered Mass %
Water	94	99.4	5.4
NaHCO ₃	93.1	99.5	6.4
Air	93.3	94.4	1.1
HCL	93.2	97.8	4.6
J.A.C	93.5	-	-
W,N,H Average	93.5	98.9	5.5
Overall Average	93.4	97.8	4.4

Table 4.7. Residual Mass by % for PC+S concrete group.

Residual Mass %			
PC+S	After Heating %	After Re-curing %	Recovered Mass %
Water	94	98.5	4.6
NaHCO ₃	93.2	98.5	5.3
Air	93.5	94	0.5
HCL	93.8	97.6	3.9
J.A.C	94	-	-
W,N,H Average	93.7	98.2	4.6
Overall Average	93.7	97.2	3.5

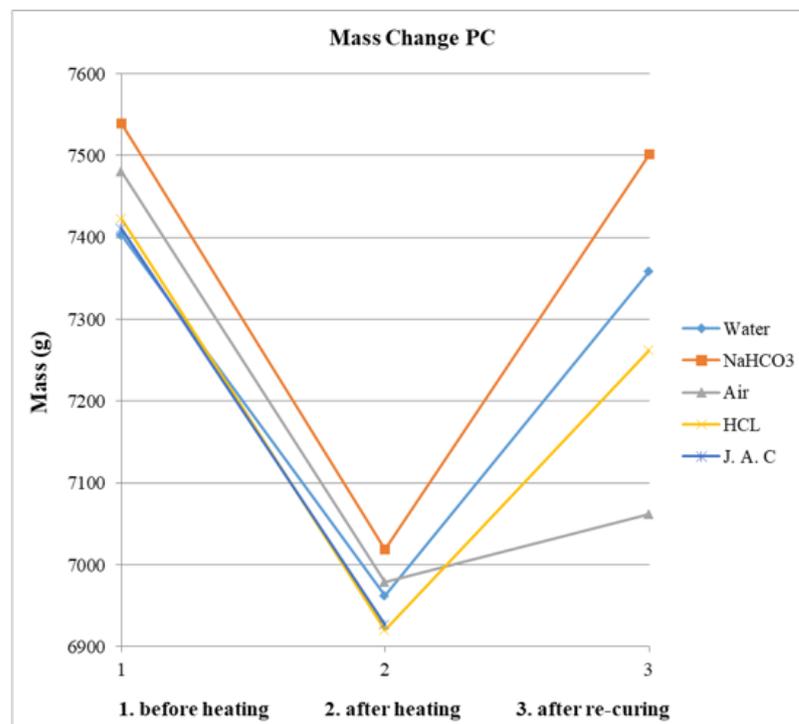


Figure 4.5. PC samples mass Changes.

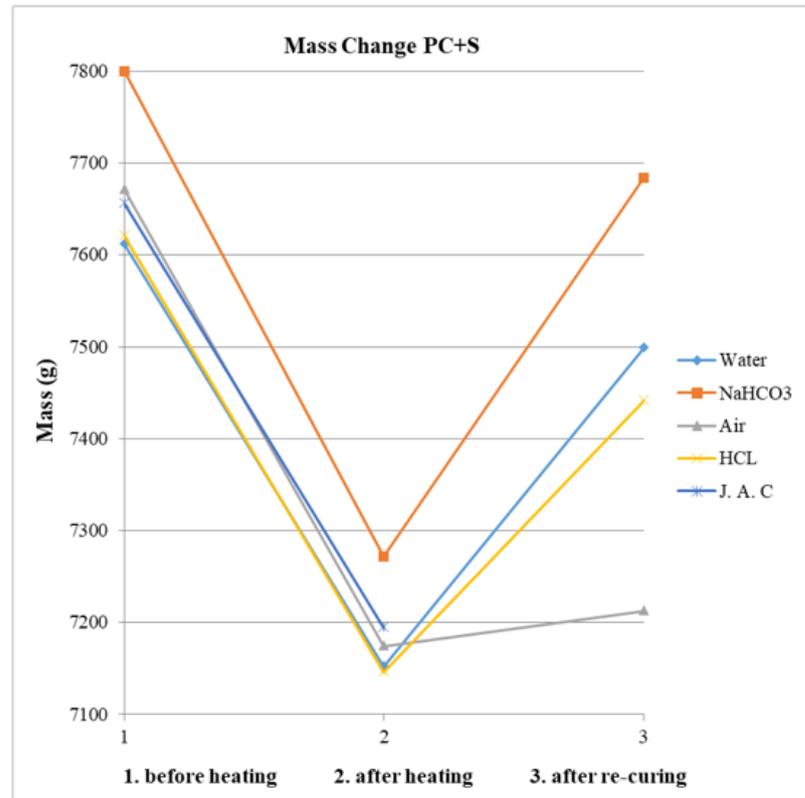


Figure 4.6. PC+S samples mass Changes.

Concrete samples lose a significant amount of their mass after being exposed to elevated temperature, as it can be seen in Table 4.6 and Table 4.7 and Figure 4.5 and Figure 4.6, average mass loss was 6.6% for samples of PC group and 6.3% for samples of PC+S group. Mass loss happens during the process of heating due to evaporation of free water at the beginning of the heating process, then at higher temperatures, chemically bonded water evaporates then decarbonation of carbonates begins at temperatures around 600°C which lead to release of carbon dioxide, mass loss continued until the end of the heating process (1000°C) [3, 11, 44]. After re-curing, PC samples regained their 97.8% of their initial mass and PC+S samples regained 97.2% of their initial mass, samples that were re-cured using water, NaHCO₃ and HCl re-curing method regained an average of 98.9% of their initial mass for PC samples and an average of 98.2% of their initial mass for PC+S samples. On the other hand, samples that were re-cured using Air re-curing method could regain 94.4% of their initial mass for PC samples and 94% for PC+S samples as it can be seen in Table 4.6 and Table 4.7 From these

values, it can be understood that air re-curing method was the least effective re-curing method among re-curing methods that were used in this study, this can also be seen in resonance frequency test results (Section 4.4) and some other studies in literature [15-18]. Meanwhile, samples that were re-cured using water and NaHCO_3 re-curing methods regained 99.4% and 99.5% of their initial mass respectively for PC samples and 98.5% and 98.5% of their initial mass respectively for PC+S samples, these values are very similar, which can be understood as, if we take post fire mass recovery into consideration, water and NaHCO_3 re-curing methods are more effective methods among re-curing methods that were used in this study.

4.6. PH And Re-Curing Liquid Level Measurement

PH and re-curing liquid level of the water, HCL and NaHCO_3 containers were measured before and after each re-curing. Reduction in re-curing liquid level in all re-curing containers was 1 cm (4.5 cm to 3.5 cm); this can be interpreted as; all samples were re-cured with the same amount of re-curing liquid.

The difference between the PH level of the re-curing liquid in the re-curing containers before and after each re-curing process is mentioned in Table 4.8.

Table 4.8. PH Change of the Re-Curing Liquid.

Concrete group	Recurring Method	pH Deference
PC	Water	+3.6 (8.4 to 12)
	HCL	+0.5 (0.5 to 1)
	NaHCO_3	+1 (8.5 to 9.5)
PC+S	Water	+4 (8.5 to 12.5)
	HCL	+0.4 (0.5 to 0.9)
	NaHCO_3	+1 (8.2 to 9.2)

Table 4.8 shows following results;

PH of tap water before re-curing was around 8, solving NaHCO_3 in the re-curing water didn't affect the pH, but when we add HCl to the re-curing water, pH decreased to 0.5, as it was expected.

During water re-curing, calcium leaching happened, as it was expected and mentioned in the introduction part, OH ions increased in water which caused increase in the pH value to around 12.

During HCl re-curing, water reacts with CaO in concrete and produces Ca(OH)_2 , also HCl reacts with CaO and produces CaCl_2 , as it was mentioned in the hypothesis of this paper, as a result, Ca(OH)_2 reduces acidity and increase pH to around 1.

During NaHCO_3 re-curing, NaHCO_3 reacts with Ca(OH)_2 and produces CaCO_3 , as it was mentioned in the hypothesis of this paper, H ions becomes free and reduce pH level and sodium produces NaOH which increases pH level, therefore the increase in pH level in NaHCO_3 re-curing method is less than the pH increase in the water re-curing method.

4.7. Residual Mechanical Properties

Fire affects the concrete morphology and internal materials that are responsible of providing mechanical performance and protecting the reinforcement bars [39]. Mechanical strength of samples from each concrete group was measured afore heating, post heating and after applying each re-curing method, results were used to evaluate the influence of each re-curing method on the mechanical properties of samples of both concrete groups, procedure was explained in Section 3.9.

Figure 4.7, Figure 4.8, Figure 4.9 and Figure 4.10 represent compressive strength and residual compressive strength of test results of samples of both PC and PC+S

concrete groups. Results show that compressive strength of samples from both concrete groups was highly affected by elevated temperature; residual compressive strength of PC samples just after cooling (J.A.C) was 49.3% and residual compressive strength of PC+S samples just after cooling (J.A.C) was 55.1%, this means that on average; all samples lost 52.2% of their compressive strength. This number further decreased when the samples were left in open air to be air re-cured, their residual compressive strength after 7 days decreased to 35.2% for PC samples and 41.1% for PC+S samples. This supports other results from other tests of this paper and some other researches in literature [15-19, 27] who report that concrete will receive further deterioration and degradation if left in open air after being exposed to elevated temperature and fire. On the other hand, results show that re-curing samples after being exposed to elevated temperature using water, HCL or NaHCO_3 re-curing methods not only stops further deterioration and degradation but it may also help in recovering mechanical strength.

Results from Figure 4.8 and Figure 4.10 show that average residual compressive strength of water, HCl and NaHCO_3 re-cured PC samples was 52.4% and for PC+S samples it was 56.1%, similar results were achieved by other tests of this research, some other works in literature also mentioned similar results for water re-cured samples [15-18]. Correspondingly, residual compressive strength of NaHCO_3 re-cured PC samples was 53.3%, which was the highest value among residual compressive strength of PC samples. Furthermore, residual compressive strength of water re-curing PC+S samples was 57.9% which was the highest value among residual compressive strength of PC+S samples. These results show that for PC samples, NaHCO_3 re-curing was more effective than other re-curing methods, but for PC+S samples, water re-curing method was more effective in recovering compressive strength of concrete after fire.

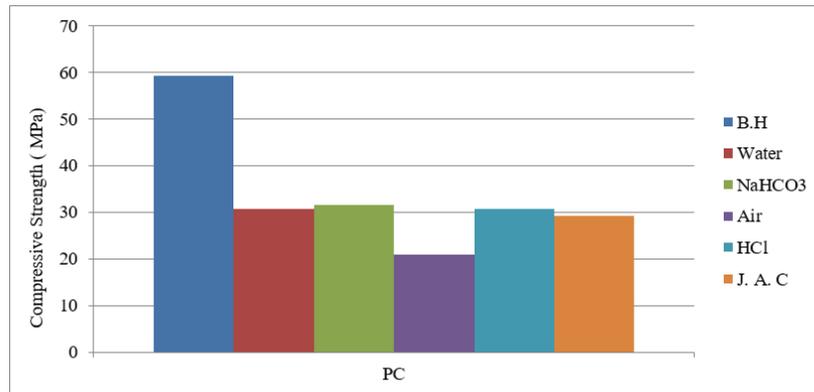


Figure 4.7. Compressive strength of PC samples

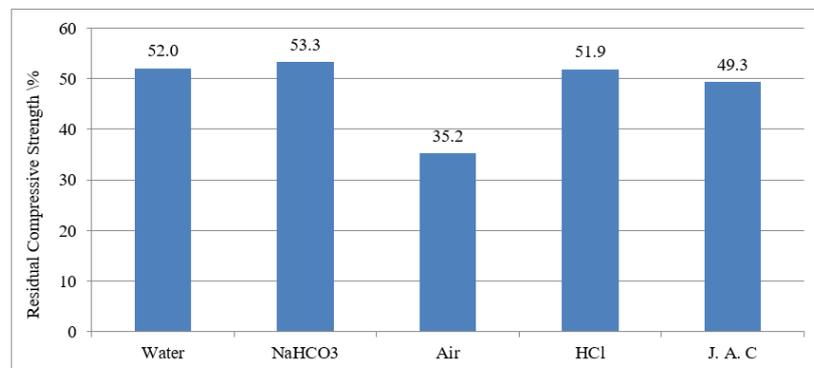


Figure 4.8. Residual compressive strength percentages of the PC concrete group.

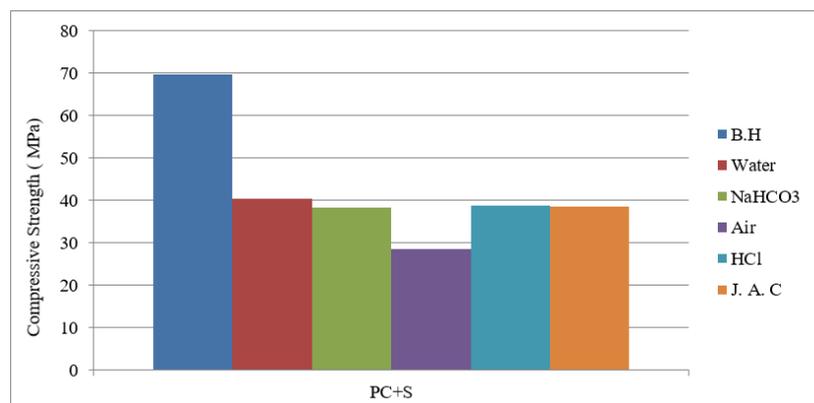


Figure 4.9. Compressive strength of PC+S samples.

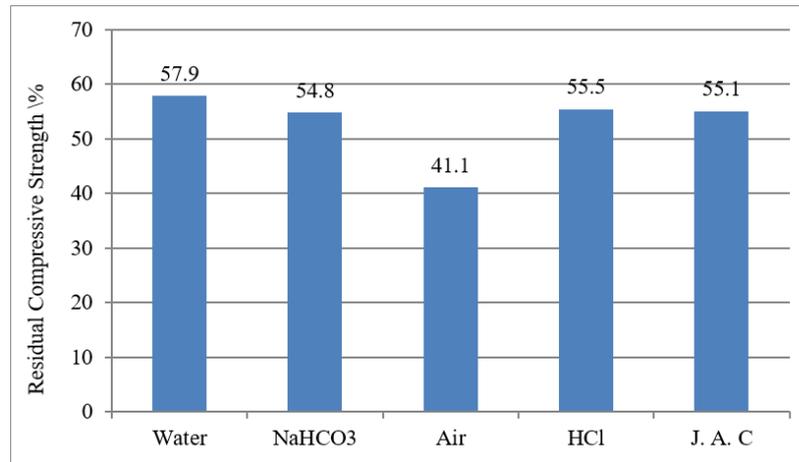


Figure 4.10. Residual compressive strength percentages of PC+S concrete group.

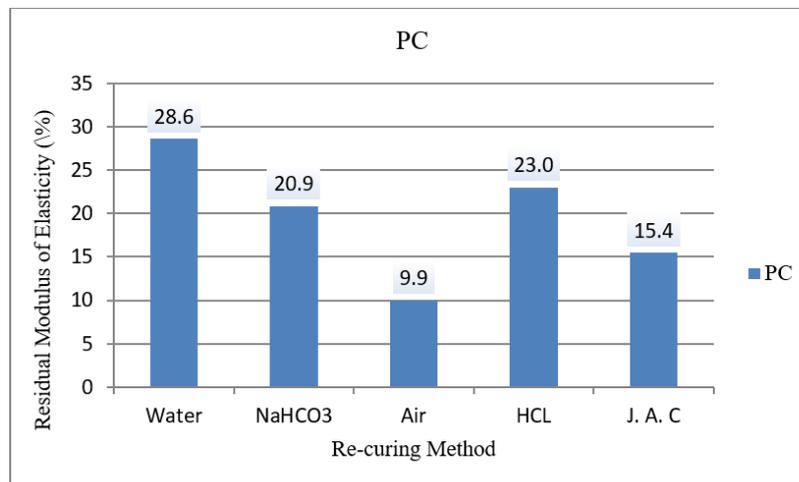


Figure 4.11. Residual Modulus of Elasticity % of PC samples.

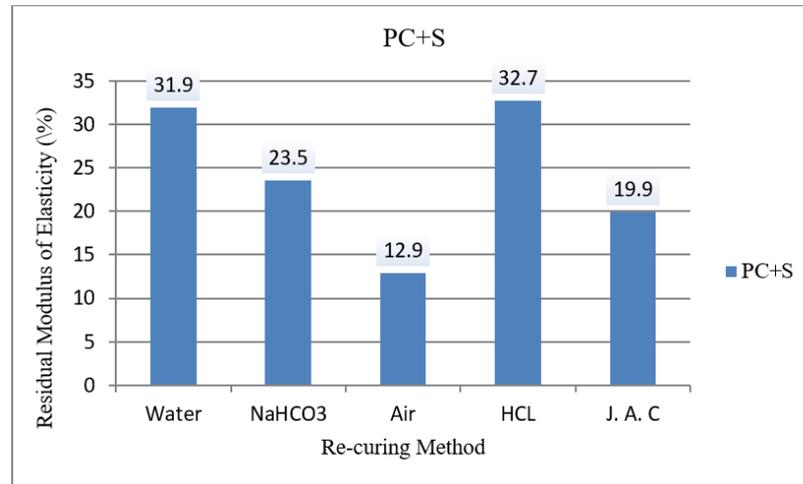


Figure 4.12. Residual Modulus of Elasticity % of PC+S samples.

Modulus of elasticity of samples was calculated while measuring their compressive strength. Figure 4.11 and Figure 4.12 represent residual modulus of elasticity percentages for PC and PC+S samples respectively, results show that exposing concrete samples to elevated temperature highly affected the modulus of elasticity of the samples, average residual modulus of elasticity of samples after heating was 17.7%, this value decreased to 11.4% when concrete samples were left in open air to be air re-cured, this result shows that post fire residual modulus of elasticity of the samples was less than post fire residual compressive strength of the samples, formation of cracks after fire and post air re-curing developed cracks can unstiffen the concrete and lead to a significant decrease in modulus of elasticity [5, 17, 54].

Average residual modulus of elasticity of PC samples that received water, NaHCO₃ and HCl re-curing was 28.6%, 20.9% and 23% respectively. These values support the idea that water re-curing method was more effective in recovering residual modulus of elasticity of PC samples. However, average residual modulus of elasticity of PC+S samples that received water, NaHCO₃ and HCl re-curing was 31.9%, 23.5% and 32.7% respectively, these values mean that water and HCl had similar effects on recovering residual modulus of elasticity of PC+S samples and they were more effective than NaHCO₃ re-curing.

Furthermore, overall average residual modulus of elasticity of all samples that received water, NaHCO_3 and HCl re-curing methods were 30.3%, 22.2% and 27.9% respectively. Residual modulus of elasticity of samples that received a re-curing method was 26.8% on average, while residual modulus of elasticity of just after cooling the samples was 17.7% on average and residual modulus of elasticity of samples that received air re-curing was 11.4% on average. These values support the fact that re-curing methods that were tested in this paper were effective in recovering residual modulus of elasticity.

4.8. Thermogravimetric Analysis (TGA) Results

Powders of TGA samples that were collected from surface and core center of samples were analyzed by a thermal analyzer, as it was explained in Section 3.11. DTG diagrams were drawn for TGA samples that were collected from surface and center of PC and PC+S samples based on results from thermogravimetric measurements as can be seen in Figure 4.13, Figure 4.14, Figure 4.15, and Figure 4.16. DTG peaks can be seen in DTG diagrams which indicate transformations, mass loss and phase changes. Peaks that appear between 350°C and 450°C correspond to portlandite ($\text{Ca}(\text{OH})_2$) dehydration and mass loss due to evaporated water [55-60]. DTG peaks that appear between 550°C and 750°C which are the highest peaks represent both calcium silicate hydrates decomposition which lead to mass loss ensuing from water loss and decarbonation of calcium carbonate (CaCO_3) which lead to mass loss due to released carbon dioxide [55, 56, 58-62].

Expected results from TGA analysis are as follow;

- For “before heating” samples, it is expected to see both $\text{Ca}(\text{OH})_2$ and CaCO_3 peaks.
- For “After heating” samples, it is expected to see reduction in both peaks at surface level and reduction in $\text{Ca}(\text{OH})_2$ peak at center level.
- For “Air re-curing” samples, it is expected to see both peaks at surface level.

- For “Water re-curing” samples, a lower $\text{Ca}(\text{OH})_2$ peak is expected due to CH leaching.
- For “ NaHCO_3 re-curing” samples, a low $\text{Ca}(\text{OH})_2$ peak is expected at surface level and a high CaCO_3 peak is expected, because NaHCO_3 reacts with CaO and cause a prominent increase in CaCO_3 content.

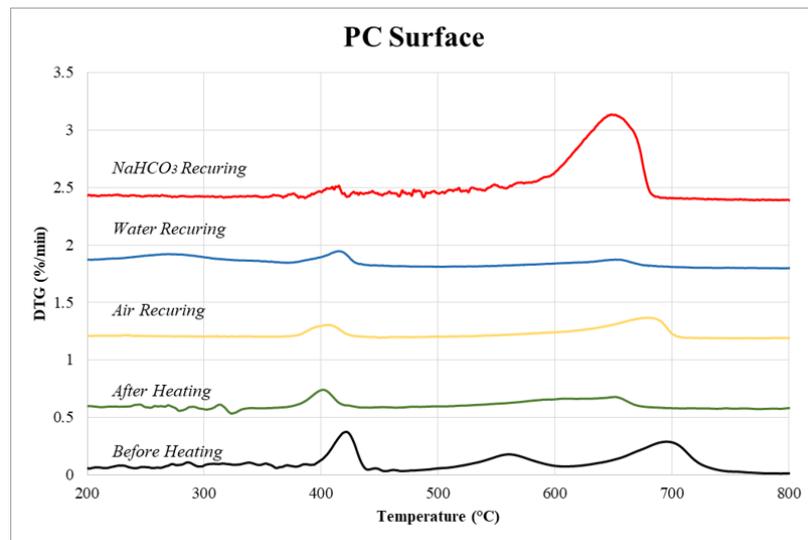


Figure 4.13. DTG diagrams of TGA samples collected from the surface of PC samples.

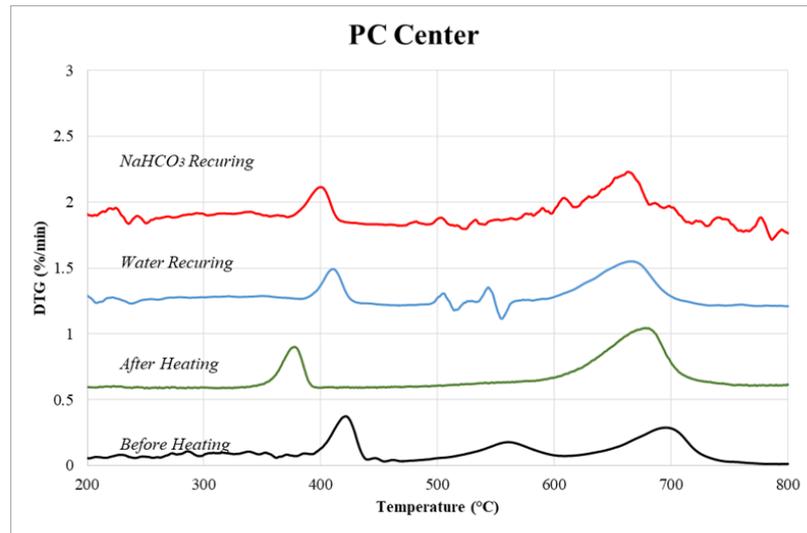


Figure 4.14. DTG diagrams of TGA samples collected from the center of PC samples.

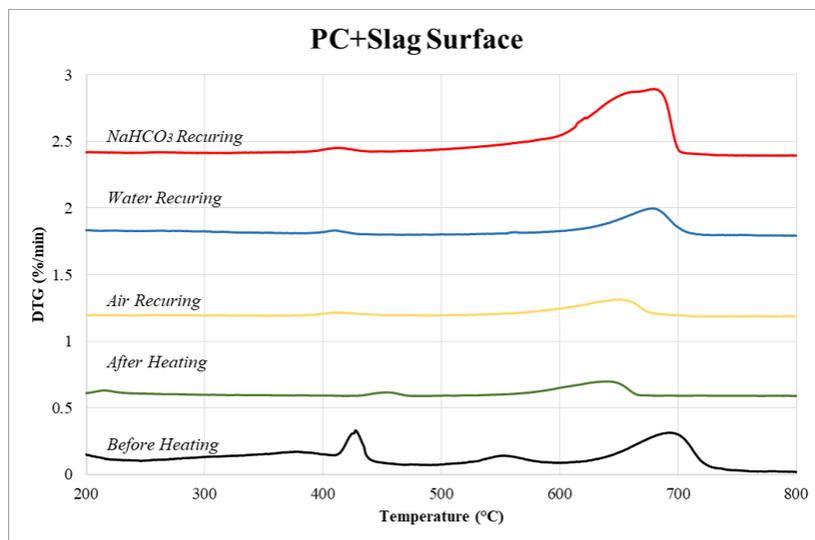


Figure 4.15. DTG diagrams of TGA samples collected from the surface of PC+S samples.

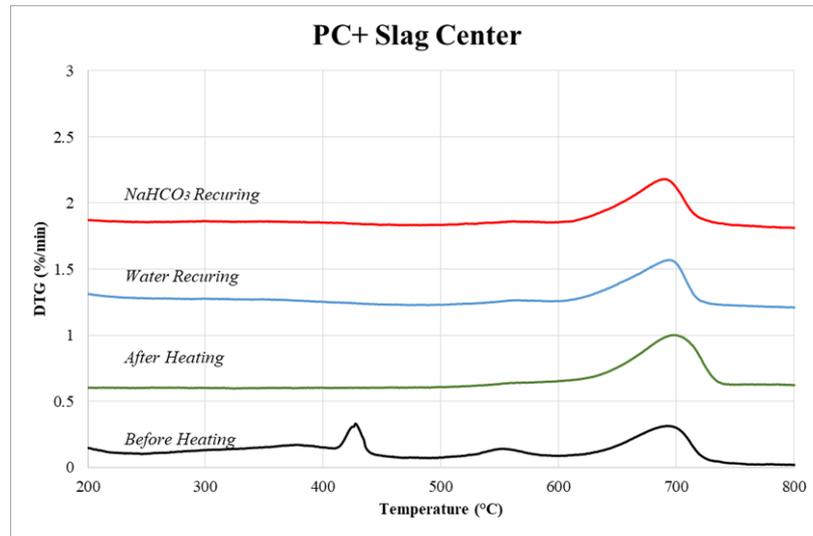


Figure 4.16. DTG diagrams of TGA samples collected from the center of PC+S samples.

Table 4.9. Calculated portlandite and calcium carbonate percentages in PC samples.

PC Samples	Level	Ca(OH) ₂	Ca(OH) ₂	CaCO ₃	CaCO ₃
		(%) 7 days	(%) 27 days	(%) 7 days	(%) 27 days
Before Heating	Surface	4.6	8.3	8.1	5.8
After Heating	Surface	0.6	0.5	1.2	0.3
	Center	2.1	0.4	7.9	2.7
Air re-curing	Surface	1.4	2.5	2.7	7.5
Water re-curing	Surface	2.8	0.1	1.6	7
	Center	3.6	6.1	9.2	8
NaHCO ₃ re-curing	Surface	0.9	-	13.7	-
	Center	4.1	-	9	-

Table 4.10. Calculated portlandite and calcium carbonate percentages in PC+S samples.

PC Samples	Level	Ca(OH) ₂ (%) 7 days	Ca(OH) ₂ (%) 27 days	CaCO ₃ (%) 7 days	CaCO ₃ (%) 27 days
Before Heating	Surface	3.4	4.3	8.9	6.4
After Heating	Surface	0	0.1	1.2	1.6
	Center	0	1.2	7.4	6.2
Air re-curing	Surface	0.6	2	1.7	2.7
Water re-curing	Surface	0.4	0.4	2.9	73.1
	Center	2.1	3.3	7.5	7.6
NaHCO₃ re-curing	Surface	0.9	-	10.8	-
	Center	2.5	-	7.6	-

DTG diagrams show that before heating samples have both peaks, while these peaks decreased or disappeared in DTG diagram of after heating samples. If we look at results of samples that were air re-cured, we can notice that there are no significant peaks differences between air re-cured samples and just after cooling samples. On the other hand, results of samples that received water or NaHCO₃ re-curing show peak pattern changes; this is more significant in results of NaHCO₃ re-cured samples, this results support the hypotheses that was mentioned in this study; NaHCO₃ re-curing affect the post fire chemical reactions in a positive way that lead to higher CaCO₃ peaks and lower Ca(OH)₂ peaks, meanwhile, higher CaCO₃ formation and lower Ca(OH)₂ formation have positive affect on the mechanical strength of concrete. Also, for NaHCO₃ re-curing, there is a very high CO₂ output, which is thought to happen due to the expected reaction that was mentioned in the introduction part (Figure 1.3. In this re-curing method, the output of Ca(OH)₂ is also low, indicating that CaO is converted to CaCO₃ instead of Ca(OH)₂. Studies in literature [48, 49] state that carbonation has a significant positive affect on the compressive strength of concrete because carbonation increase calcium carbonate and decrease calcium hydroxide inside

concrete.

We didn't perform TGA analysis for HCl samples because they would harm the TGA testing machine, when CaO reacts with HCl, CaCl₂ is formed, and the melting point of CaCl₂ is 772 Co [63], CO₂ and water from other samples evaporate, but CaCl₂ doesn't, instead, it melts and sticks to the inner parts of the testing machine and harms the TGA testing device.

We don't see a lot of changes in CaCO₃ peak in the center because temperature of the center of the samples was lower than the surface, so the center of the samples wasn't exposed to high temperatures compared to the surface.

On the surface of water re-cured samples, it can be noticed that (Ca(OH)₂) peak is much lower, because during water re-curing, Ca(OH)₂ is leaching in water, so it doesn't form, instead, calcium silicates are converted to C-S-H gel. So we can attribute the increase in strength and the decrease of surface cracks of the water re-cured samples to the restoration of the C-S-H phase and elimination of negative impact of expansive Ca(OH)₂ formation.

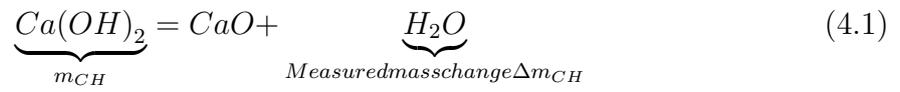
Amount of portlandite (Ca(OH)₂) and calcium carbonate (CaCO₃) in samples were calculated for before heating, after heating, 7 days air re-cured, 7 days water re-cured and 7 days NaHCO₃ re-cured samples using, Table 4.9 and Table 4.10 show their percentages in PC and PC+S samples respectively, 27 re-curing results from a research in literature [12] are also shown in Table 4.9 and Table 4.10 for the purpose of comparison, Table 4.9 and Table 4.10 show following results:

- For “before heating” samples; portlandite (Ca(OH)₂) and calcium carbonate (CaCO₃) originally exist in samples from both concrete groups, but the amount of portlandite (Ca(OH)₂) in PC samples were nearly 26% higher than the amount of portlandite (Ca(OH)₂) in PC+S samples.
- For “After heating” samples; at the surface level, amount of portlandite (Ca(OH)₂)

is close to zero and amount of calcium carbonate (CaCO_3) is greatly reduced, this happened because the surface level of the samples was exposed to a very high temperature (1000 Co), and gels and crystals deteriorate at this temperature. On the other hand, the amount of calcium carbonate (CaCO_3) in the center of the samples was slightly decreased, due to the fact that the temperature at the center of the samples was lower than the surface level. Similar situation was reported by a study in literature [12].

- For “Air re-curing” samples; amount of portlandite (Ca(OH)_2) and calcium carbonate (CaCO_3) increased on the surface level of both PC and PC+S samples. The surface level of concrete was exposed to 1000 Co and became very weak, meanwhile, Amount of portlandite (Ca(OH)_2) continue to increase on the surface level as it is formed by a reaction between CaO and water particles in air which is an expansive reaction and result in volume increase, this can be one of the main reasons of surface cracks, performance weakening, post fire degradation and failure of air re-cured concrete samples [3, 10-12].
- For “Water re-curing” samples; amount of portlandite (Ca(OH)_2) on the surface level decreased for PC samples and almost disappeared for PC+S samples. This decrease is believed to happen because of portlandite leaching in water, newly formed portlandite particles dissolves in the re-curing water, as a result, negative impact of expansive CH formation is eliminated, calcium silicates are converted to C-S-H gel and C-S-H phase is restored, surface cracks decreased and mechanical performance increased. Research in literature report that these values were almost zero after 27 days (as it can be seen in Table 4.9 and Table 4.10) of post fire water re-curing [12, 16, 18] this may be due to the fact that portlandite leaching in water is continuous. Moreover, amount of portlandite at the center of samples increased, but this increase at the center is believed to have less negative impact on the mechanical performance and crack formation compared to the surface level due to the fact that the center of the samples were exposed to lower temperatures and received less damage, also expansive reaction of (Ca(OH)_2) formation is restricted from all dimensions by the inner parts of concrete.
- For “ NaHCO_3 re-curing” samples; amount of portlandite (Ca(OH)_2) on the sur-

face level is very low, amount of portlandite on the surface level of NaHCO_3 re-cured PC+S samples are lower (0.9%) than the amount of portlandite on the surface level of water re-cured PC+S (2.8%). Also, amount of calcium carbonate (CaCO_3) on the surface level of NaHCO_3 re-cured PC and PC+S samples are 13.7% and 10.8%, respectively, which are much higher than the amount of calcium carbonate (CaCO_3) on the surface level of water re-cured, air re-cured and before heating samples, which means that NaHCO_3 re-curing affect the post fire chemical reactions in a positive way as NaHCO_3 react with CaO , as a result, CaCO_3 is formed instead of Ca(OH)_2 , so negative impact of expansive CH formation is eliminated, calcium silicates are converted to C-S-H gel and C-S-H phase is restored, surface cracks decreased and mechanical performance recovered as it was expected in the hypothesis of this thesis and as given by



$$\mathbf{m}_{CH} = \Delta m_{CH} \times \frac{74g/mol}{18g/mol} \quad (4.3)$$

$$\mathbf{m}_{CC} = \Delta m_{CC} \times \frac{100g/mol}{44g/mol}. \quad (4.4)$$

5. CONCLUSION

For the purpose of studying and investigating the behavior of concrete after fire and comparing different post fire re-curing techniques, 2 groups of concrete were produced, which were PC concrete group (prepared using ordinary Portland cement) and PC+S concrete group (GGBFS was used as a binding material alongside with OPC). Cubic and prism samples were prepared from each concrete group. Chemical admixture and polypropylene fiber were used in all samples. After casting, Concrete samples were water cured for 28 days and then they were left in room temperature for 6 months.

Both destructive and non-destructive investigations were conducted to measure their mechanical properties in each stage; afore heating, post heating and after applying each re-curing method. One face of samples was heated up to 1000 oC for duration of 200 minutes in an electrical furnace to mimic a fire scenario, then the samples were left in the furnace to cool down. Four post fire re-curing methods were applied for 7 days, which were water, HCl, air and NaHCO₃ re-curings. Samples were divided to 5 groups: just after cooling (J.A.C), water, HCl, air and NaHCO₃ re-curing samples.

Compressive strength of all samples were measured at every stage, average compressive strength of PC samples before heating was 59.2 MPa, while the average compressive strength of PC+S samples before heating was 69.7 MPa, using GGBFS as partial cementitious material replacement alongside with OPC increased the compressive strength as it was expected. Just after cooling(J.A.C) average residual compressive strength of PC samples was 49.3% of the initial before heating value, while Just after cooling (J.A.C) average residual compressive strength of PC+S samples was 55.1%, these results may suggest that using GGBFS helped in improving fire performance of concrete samples to some extent since the just after cooling average residual compressive strength of PC+S samples was higher than the just after cooling average residual compressive strength of PC samples.

On average, just after cooling residual compressive strength, residual static modulus of elasticity and dynamic modulus of elasticity of all samples were 52.2% and 17.7% 17.6% respectively, which means samples lost nearly half of their compressive strength and more than 80% of their modulus of elasticity after they were exposed to elevated (1000 oC) temperature for 200 minutes. Residual compressive strength, residual static modulus of elasticity decreased to 38.1%, and 11.4% after samples were left in room temperature to be air re-cured for 7 days, which means on average samples lost 14.1% of their compressive strength and 6.3% of their static modulus of elasticity in this duration, researches in literature state that these values continue to decrease, post fire concrete samples that were air re-cured continue to lose their mechanical strength [12], this may result in post fire collapse and cause disaster in buildings and structures [11, 19, 27, 61]. During air re-curing period, expansion reaction happens and CaO undergoes a phase change to Ca(OH)_2 , this results in further cracking and degradation of concrete and this expansion reaction can be one of the main reasons of the reduction of mechanical strength of concrete post fire and during air re-curing process. PC sample's just after cooling average residual compressive strength and static modulus of elasticity were 49.3% and 15.4% respectively, while just after cooling average residual compressive strength and residual static modulus of elasticity of PC+S samples were 55.1% and 19.9% respectively, also average residual compressive strength and residual static modulus of elasticity for air re-cured PC samples were 35.2% and 9.9% respectively and for air re-cured PC+S samples they were 41.1% and 12.9% respectively.

Mass of samples was recorded afore heating, post heating and after applying each re-curing method. On average, PC samples lost 6.6% of their mass after heating and PC+S samples lost 6.3% of their mass after heating. Mass loss happens mainly due to evaporation of water during heating process, as free water evaporation starts at 100 OC, then chemically bonded water evaporation begins and increases with temperature increase, also evaporation of CO_2 due to decarbonation of CaCO_3 begins after 600 oC. Air re-cured PC and PC+S samples recovered 1.1% and 0.5% of their masses respectively, while water, NaHCO_3 and HCl re-cured PC samples recovered 5.4%, 6.4% and 4.6% of their masses respectively and water, NaHCO_3 and HCl re-cured PC+S

samples recovered 4.6%, 5.3% and 3.9% of their masses respectively. NaHCO_3 re-cured samples recovered 5.8% of their mass which was the highest value compared to results from other re-curing methods. Generally, samples that were re-cured using water, NaHCO_3 and HCl re-curing methods recovered 5% of their masses on average, while air re-cured samples only recovered 0.8% of their masses on average.

Residual compressive strength of PC samples that received water re-curing, NaHCO_3 re-curing and HCl re-curing were 52%, 53.3% and 51.9% respectively, while residual compressive strength of PC+S samples that received water re-curing, NaHCO_3 re-curing and HCl re-curing were 57.9%, 54.8% and 55.5% respectively. Furthermore, overall average residual compressive strength of all samples that received water, NaHCO_3 and HCl re-curing were 54.9%, 54% and 53.7% respectively and overall average residual compressive strength of re-cured samples was 54.2%, which means that overall average residual compressive strength of samples that were re-cured using water, NaHCO_3 and HCl was 16.1% higher than average residual compressive strength of air re-cured samples.

Residual modulus of elasticity of PC samples that received water, NaHCO_3 and HCl re-curing were 28.6%, 20.9% and 23% respectively. Meanwhile, residual modulus of elasticity of PC+S samples that received water, NaHCO_3 and HCl re-curing were 31.9%, 23.5% and 32.7% respectively. Residual modulus of elasticity of samples that received water, NaHCO_3 and HCl re-curing was 26.8% on average, while residual modulus of elasticity of just after cooling samples was 17.7% on average and residual modulus of elasticity of air re-cured samples was 11.4% on average, which means that overall average residual modulus of elasticity of samples that received water, NaHCO_3 and HCl re-curing was 15.4% higher than average residual compressive strength of air re-cured samples.

Residual Dynamic modulus of elasticity of samples that received water, NaHCO_3 and HCl re-curing was 45.2% on average while residual Dynamic modulus of elasticity of samples that were air re-cured was 17.4%.

Results of this study lead us to the following conclusions:

- For recovering the compressive strength of samples after fire; NaHCO_3 re-curing method was more effective for PC samples and water re-curing was more effective for PC+S samples compared to other re-curing methods.
- For recovering dynamic Young's modulus of elasticity of samples post fire; water re-curing method was more effective for PC samples and HCl re-curing was more effective for PC+S samples compared to other re-curing methods.
- Using water, NaHCO_3 or HCl post fire re-curing methods can be effective in stopping degradation of concrete after fire and recovering concrete's compressive strength and modulus of elasticity, which may eliminate or decrease the risk of post fire collapse and failure of concrete.
- PC samples received more damage in both after fire and after air re-curing process compared to PC+S samples [12].
- PC samples lost more mass after fire compared to PC+S samples.
- Water re-curing method was more effective in recovering residual static modulus of elasticity of PC samples and water and HCl had similar effects on recovering residual static modulus of elasticity of PC+S samples and they were more effective than NaHCO_3 re-curing.
- Using water, NaHCO_3 or HCl post fire re-curing methods can be effective in recovering the mass of concrete after fire.
- NaHCO_3 re-curing affect the post fire chemical reactions in a positive way as NaHCO_3 react with CaO , as a result, CaCO_3 is formed instead of Ca(OH)_2 that lead to higher CaCO_3 peaks and percentages and lower Ca(OH)_2 peaks and percentages compared to other re-curing methods. Higher CaCO_3 formation and lower Ca(OH)_2 formation have positive affect on the residual mechanical strength, as negative impact of expansive CH formation is eliminated, calcium silicates are converted to C-S-H gel and C-S-H phase is restored, surface cracks decreased and mechanical performance recovered as it was expected in the hypothesis of this thesis. carbonation has a significant positive affect on the compressive strength of concrete because carbonation increases calcium carbonate and decreases calcium

hydroxide inside concrete [48, 49].

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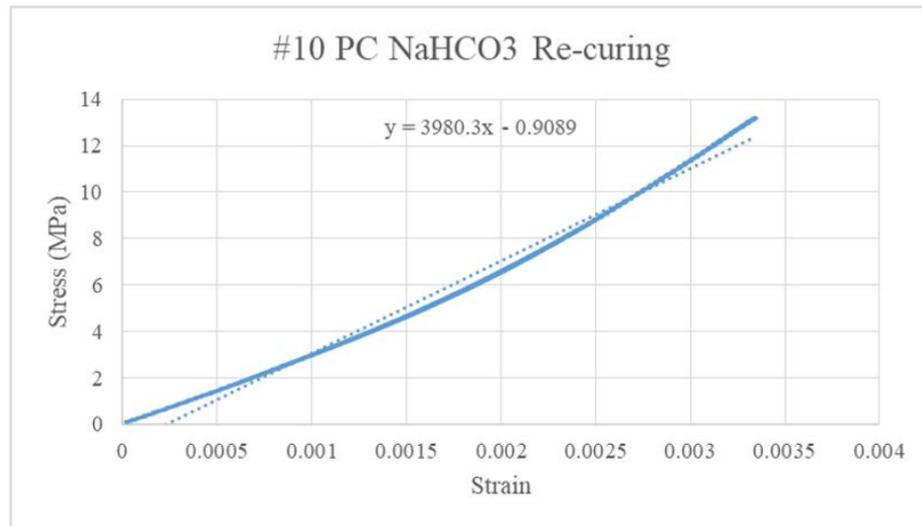
APPENDIX A: MODULUS OF ELASTICITY

Figure A.1. Modulus of Elasticity 1.

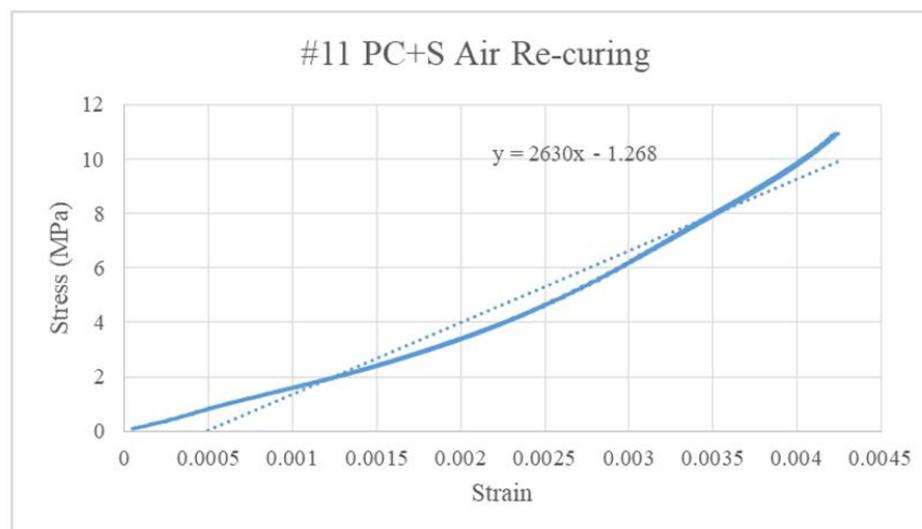


Figure A.2. Modulus of Elasticity 2.

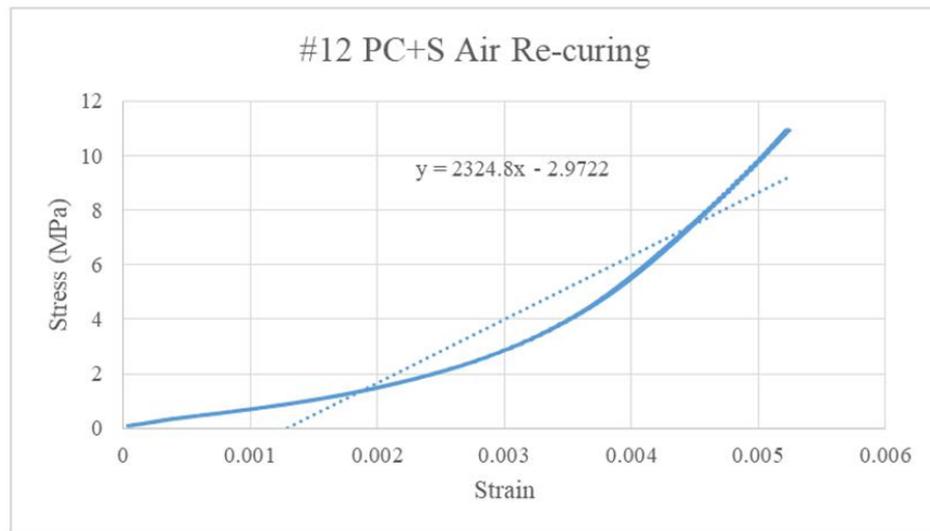


Figure A.3. Modulus of Elasticity 3.

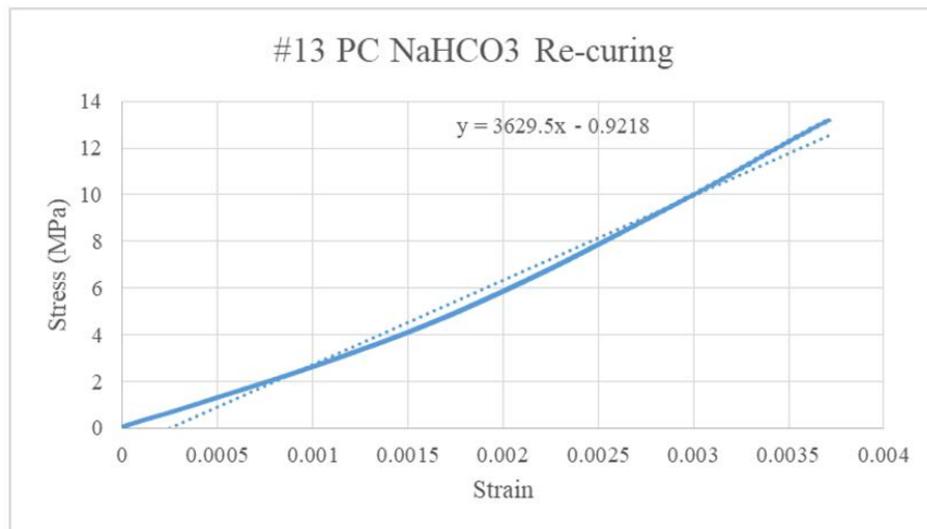


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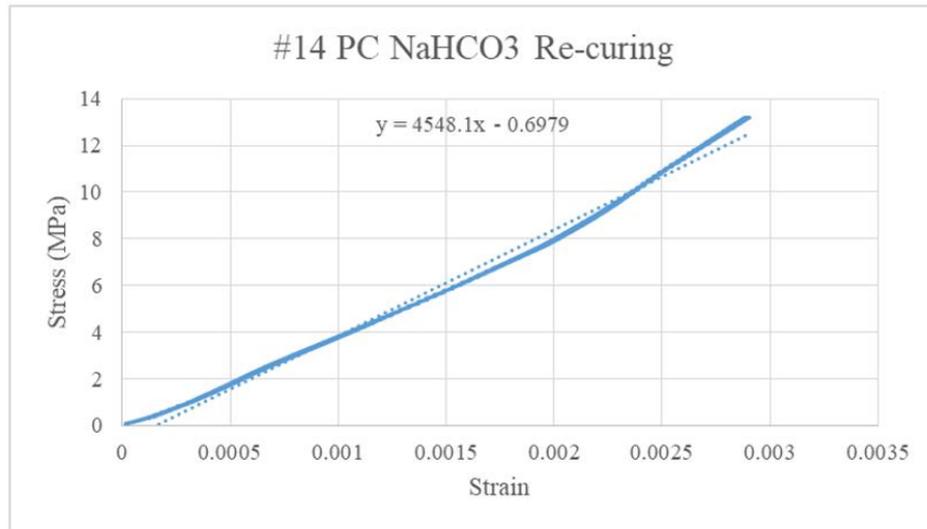


Figure A.5. Modulus of Elasticity 5.

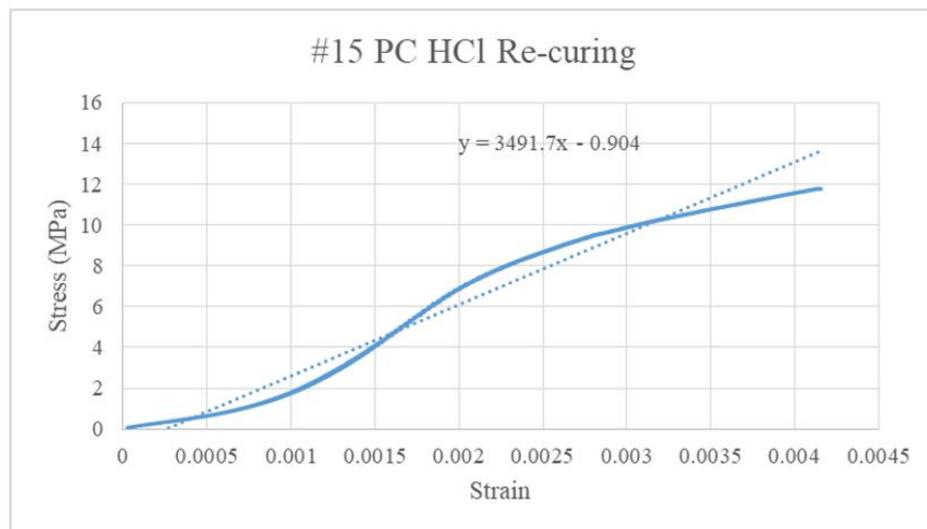


Figure A.6. Modulus of Elasticity 6.

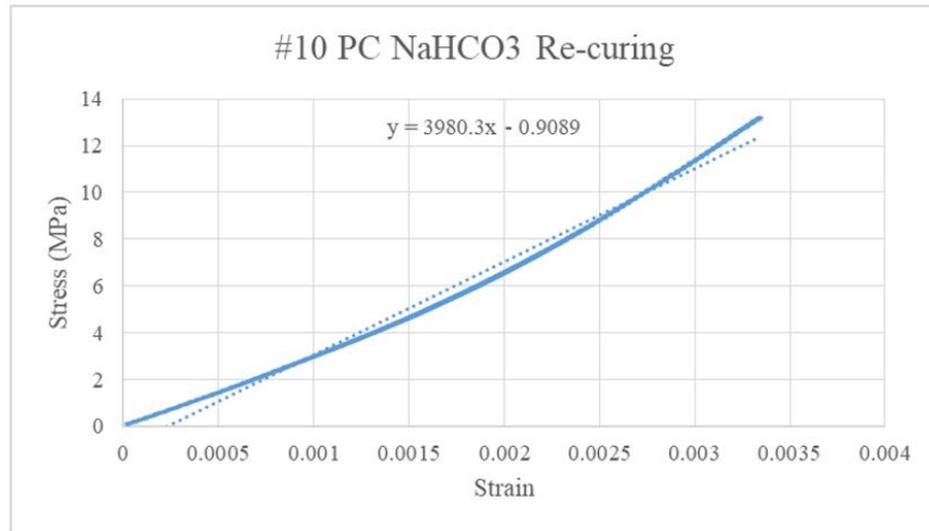


Figure A.7. Modulus of Elasticity 7.

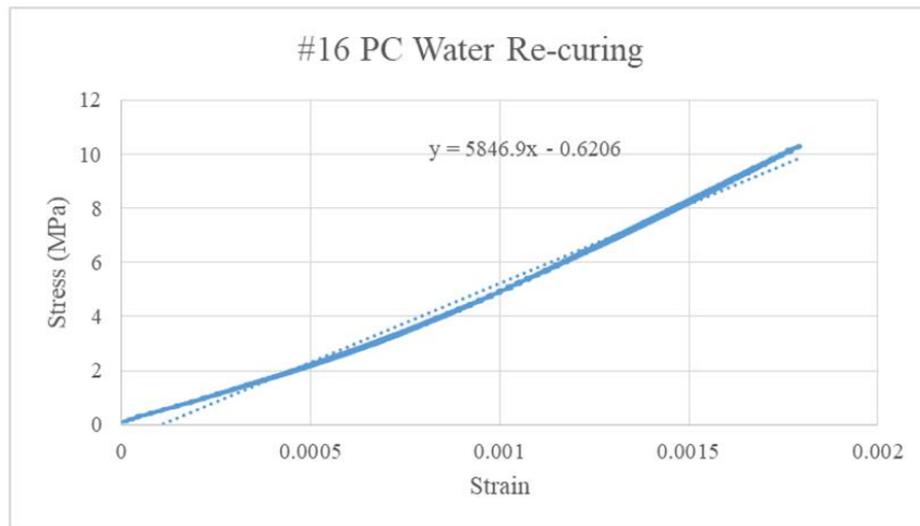


Figure A.8. Modulus of Elasticity 8.

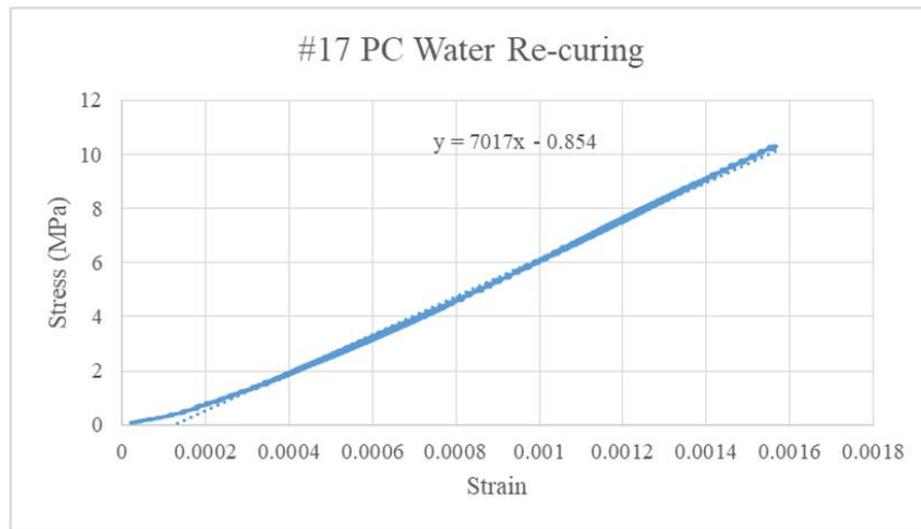


Figure A.9. Modulus of Elasticity 9.

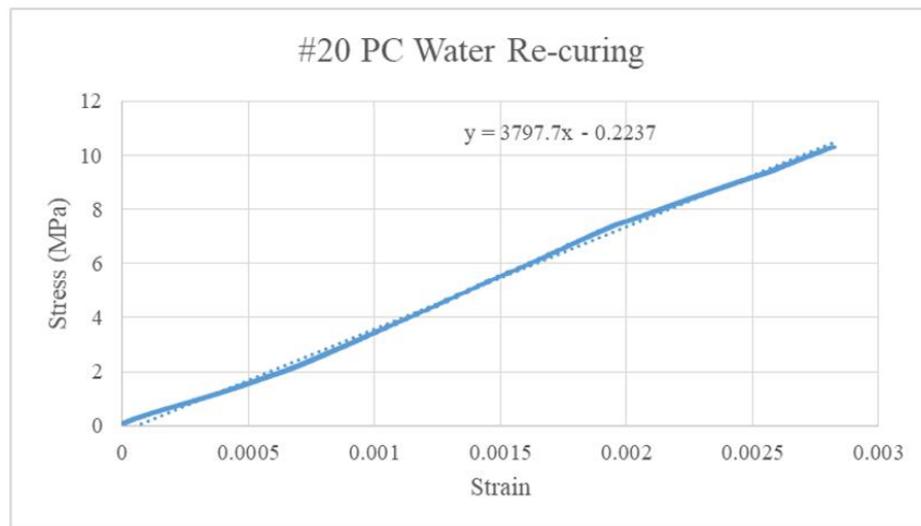


Figure A.10. Modulus of Elasticity 10.

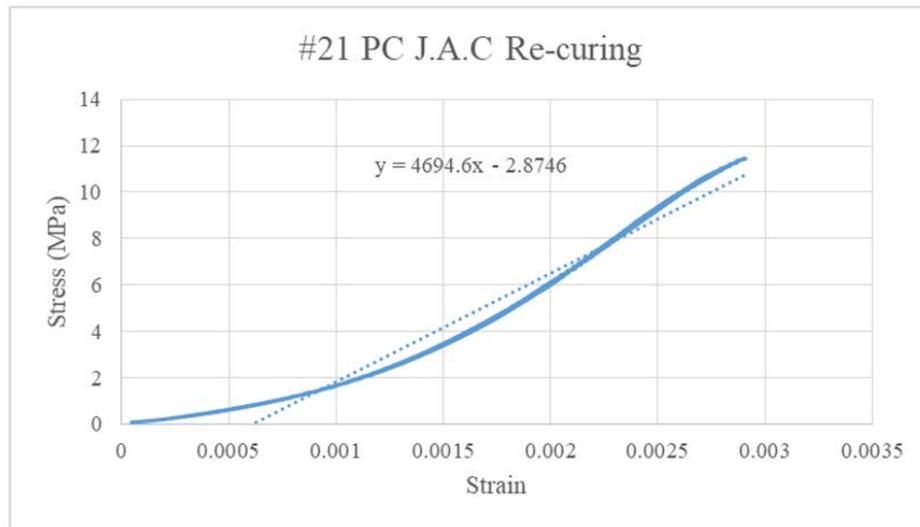


Figure A.11. Modulus of Elasticity 11.

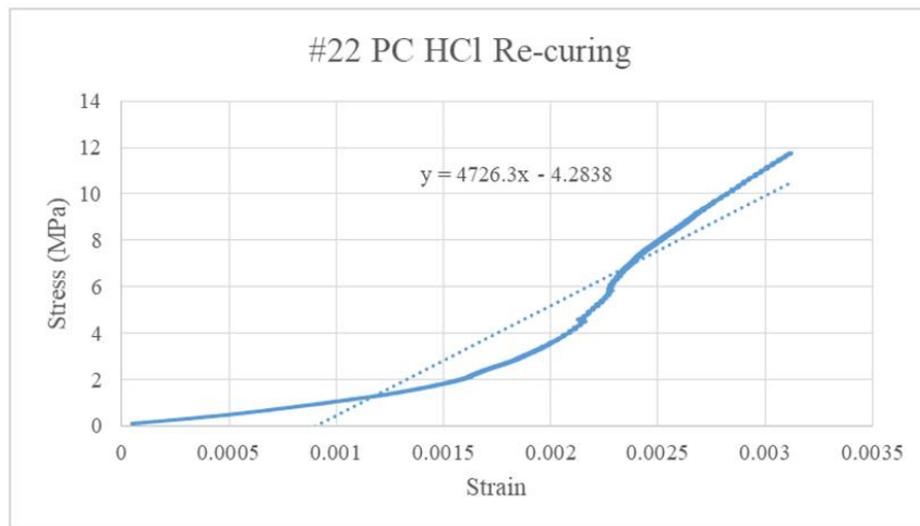


Figure A.12. Modulus of Elasticity 12.

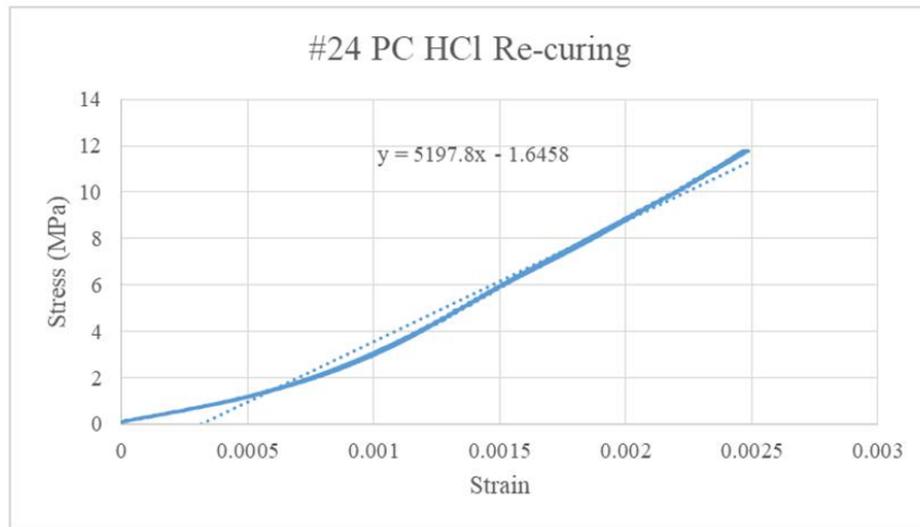


Figure A.13. Modulus of Elasticity 13.

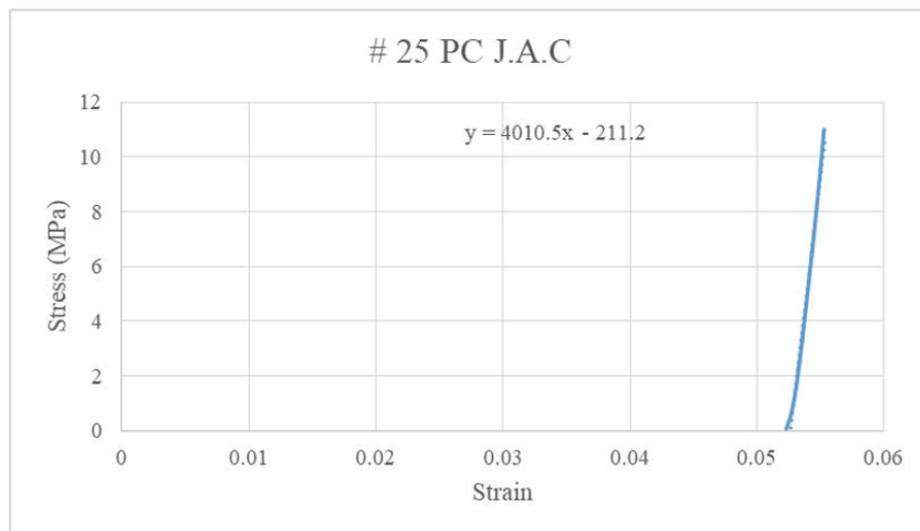


Figure A.14. Modulus of Elasticity 14.

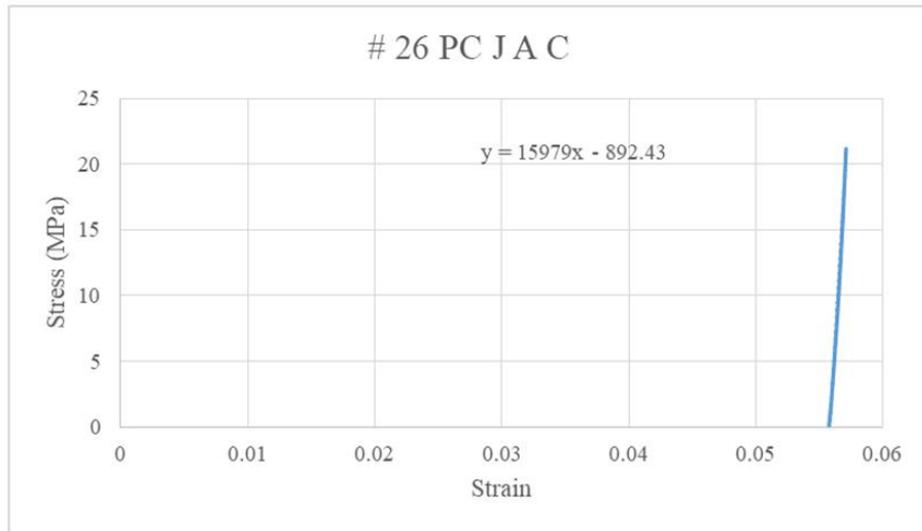


Figure A.15. Modulus of Elasticity 15.

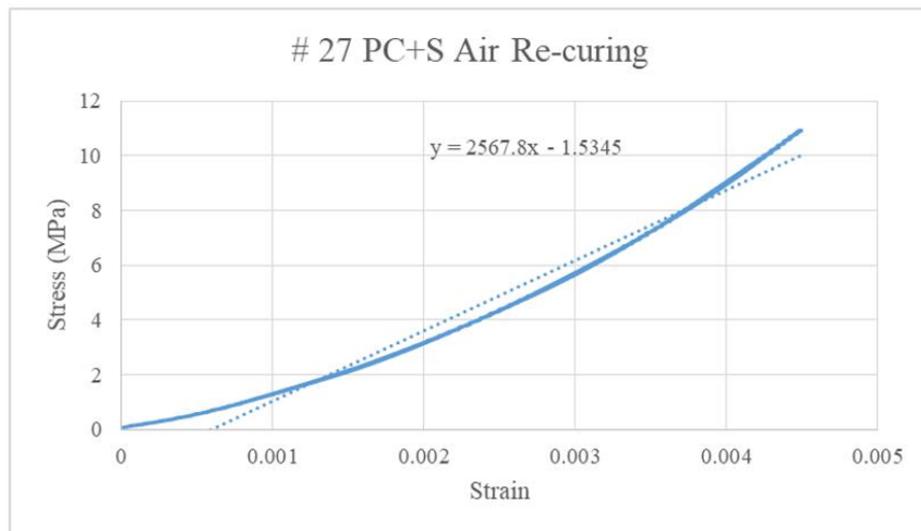


Figure A.16. Modulus of Elasticity 16.

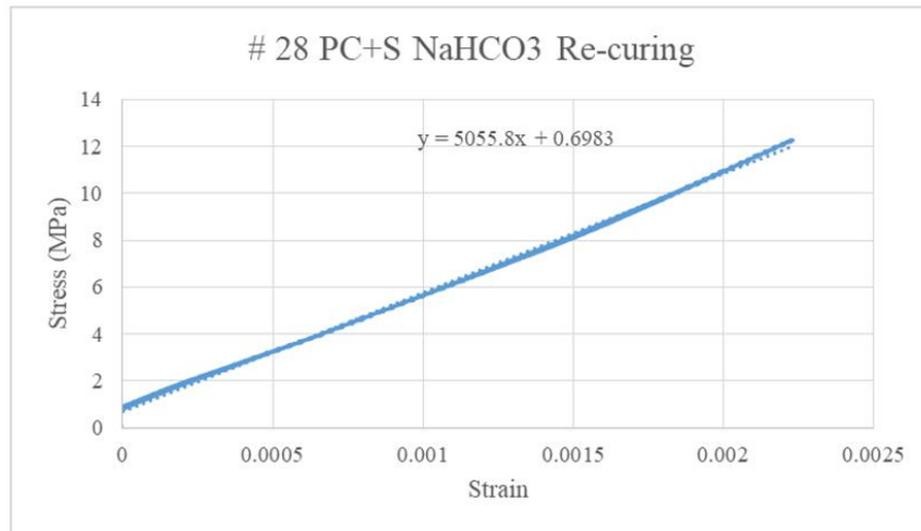


Figure A.17. Modulus of Elasticity 17.

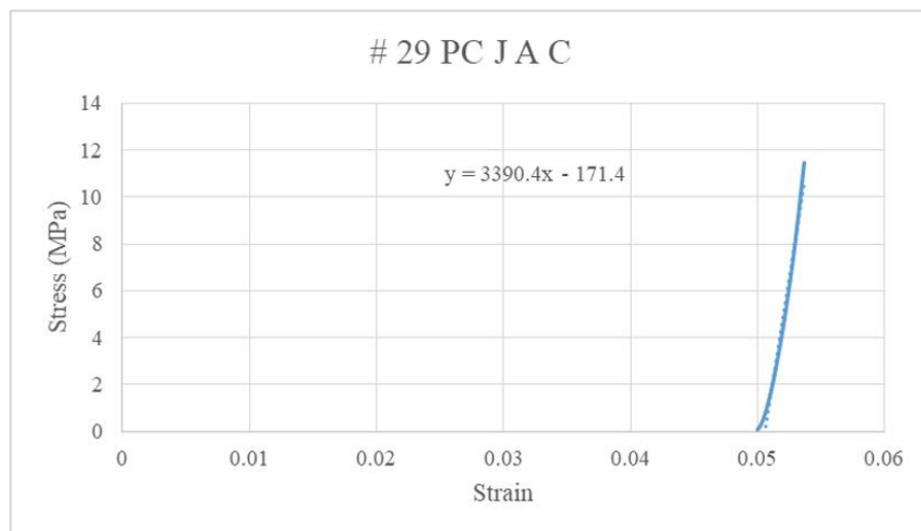


Figure A.18. Modulus of Elasticity 18.

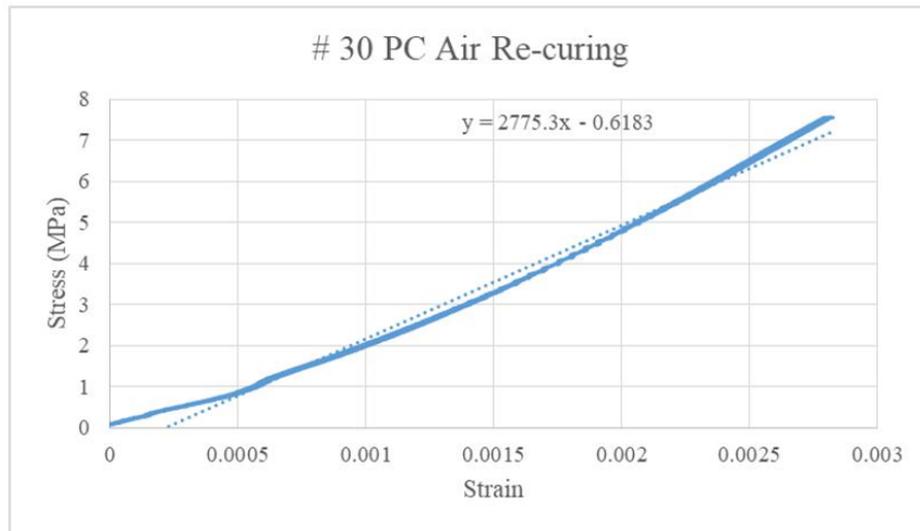


Figure A.19. Modulus of Elasticity 19.

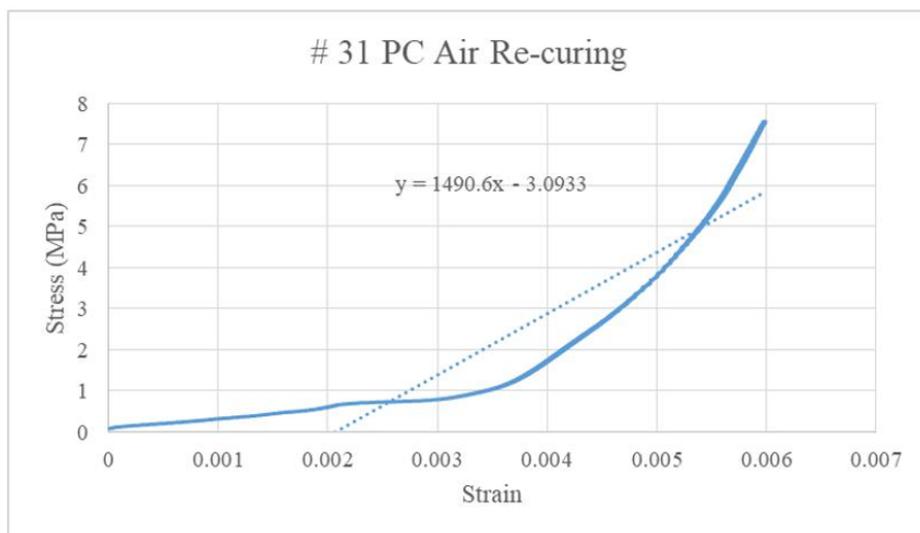


Figure A.20. Modulus of Elasticity 20.

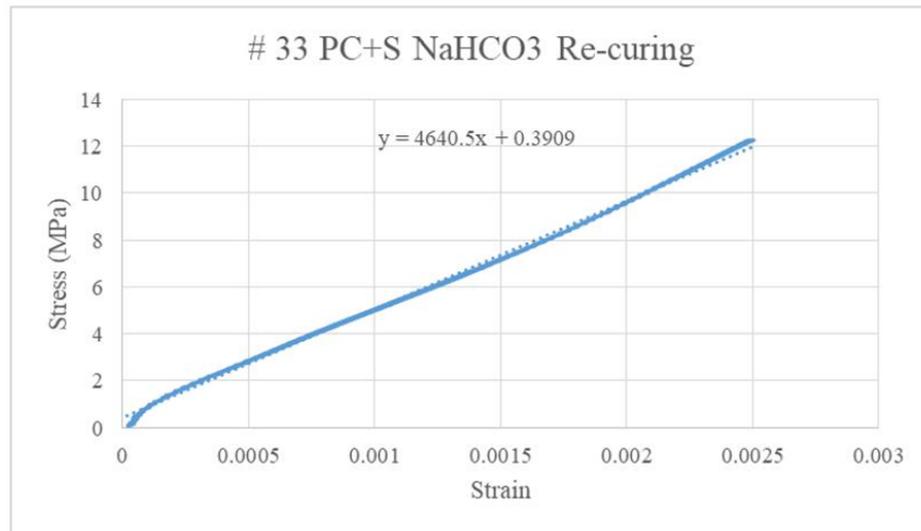


Figure A.21. Modulus of Elasticity 21.

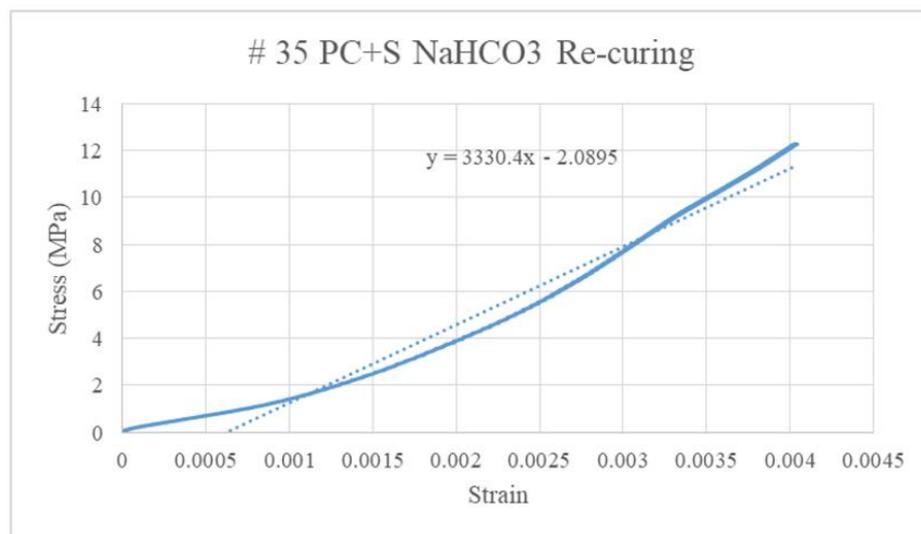


Figure A.22. Modulus of Elasticity 22.

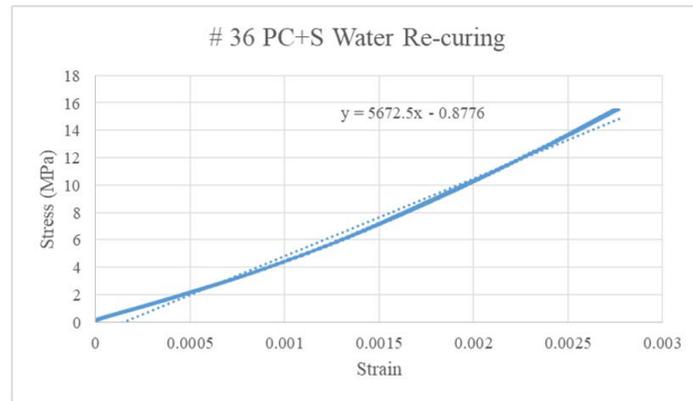


Figure A.23. Modulus of Elasticity 23.

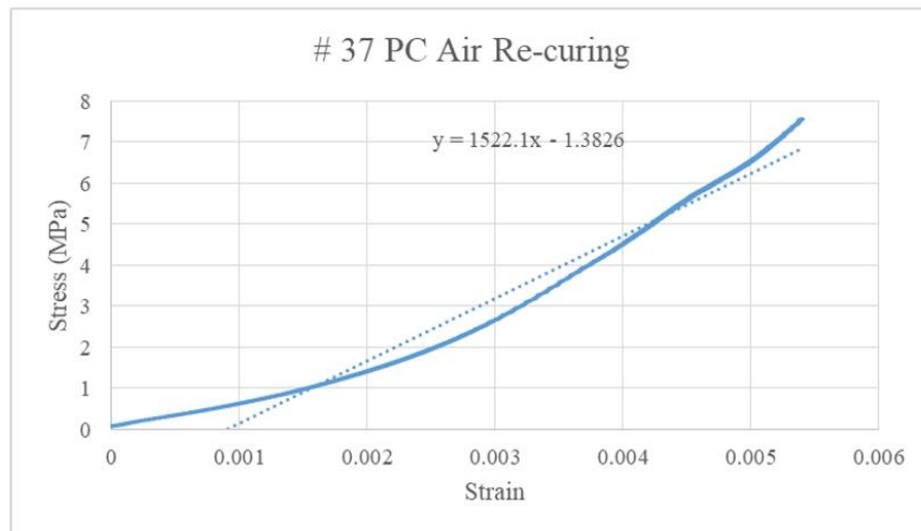


Figure A.24. Modulus of Elasticity 24.

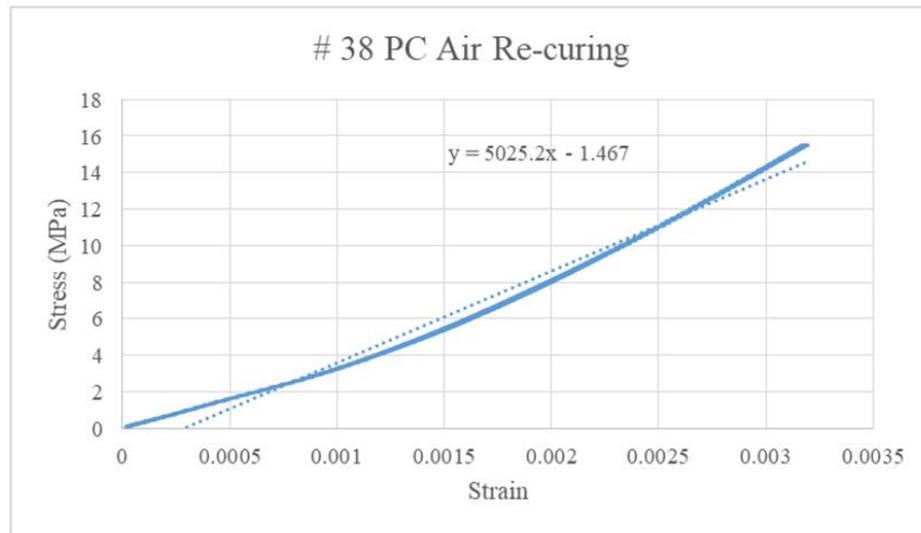


Figure A.25. Modulus of Elasticity 25.

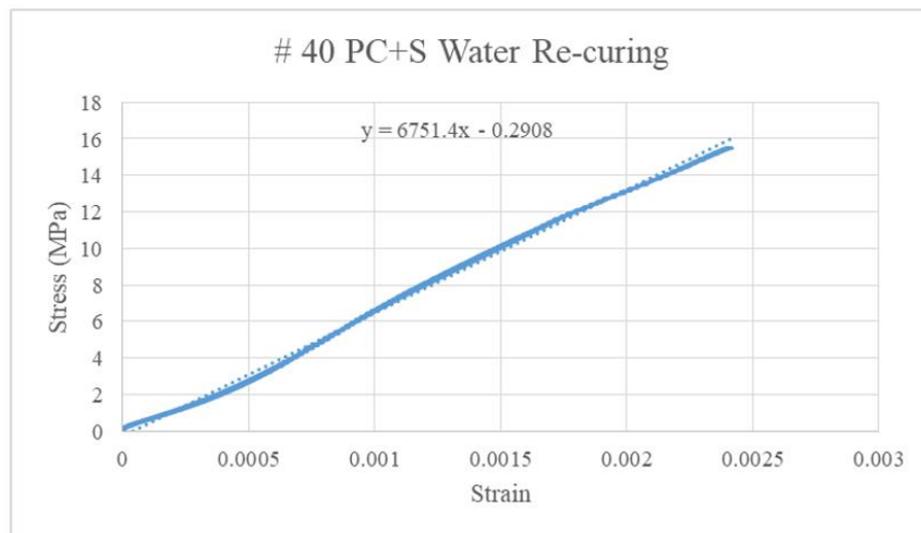


Figure A.26. Modulus of Elasticity 26.

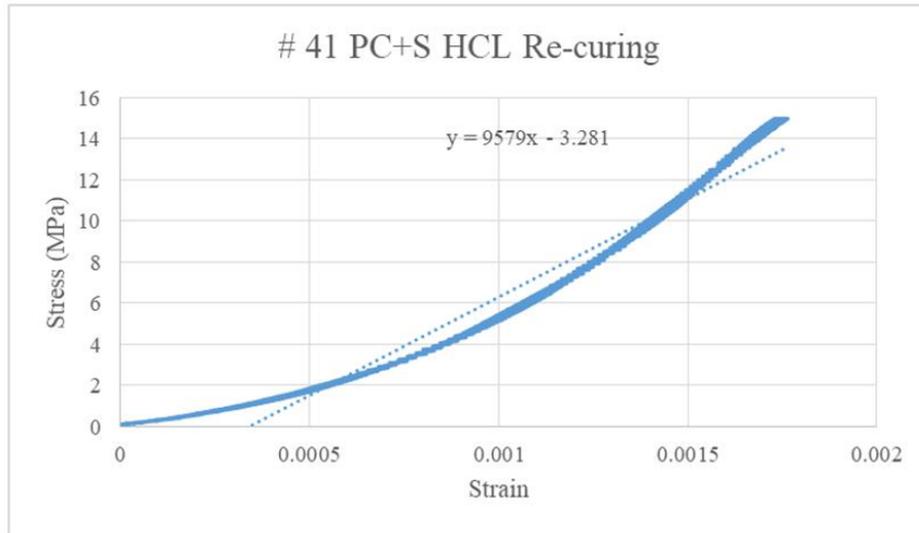


Figure A.27. Modulus of Elasticity 27.

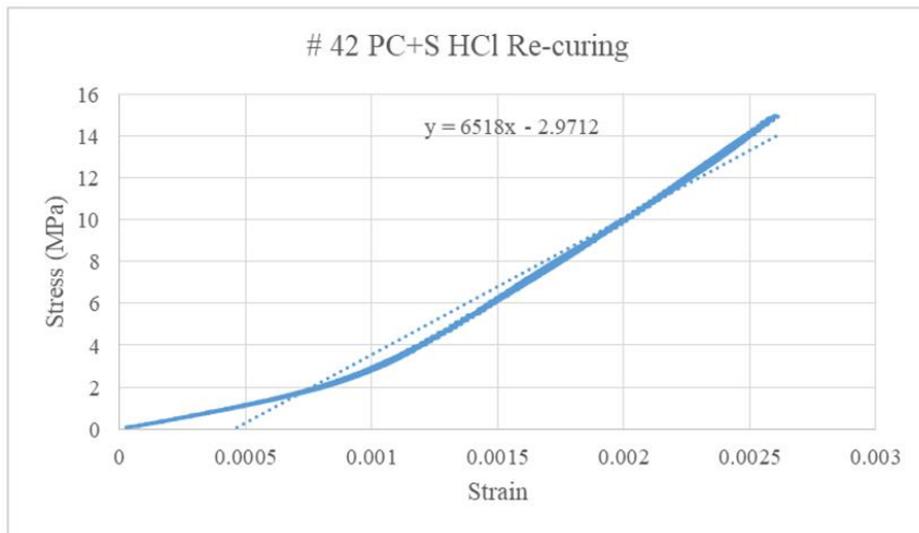


Figure A.28. Modulus of Elasticity 28.

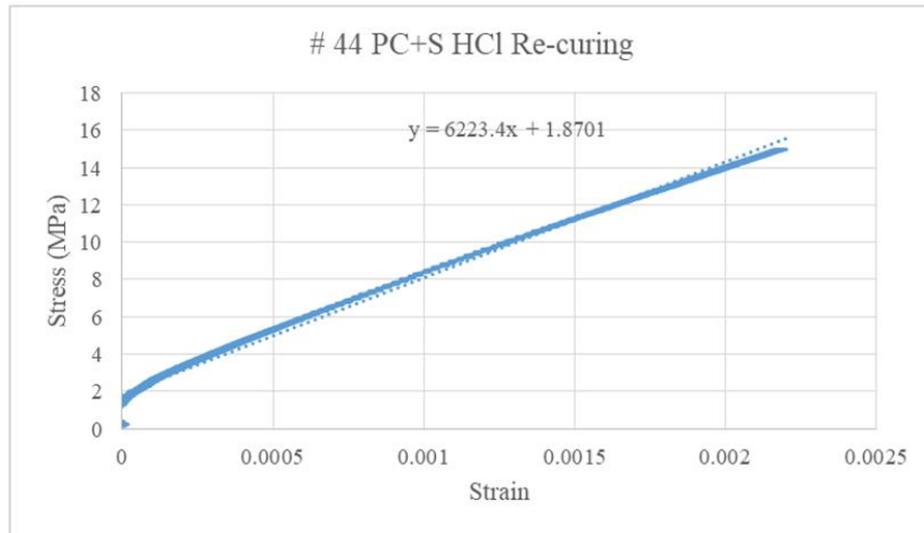


Figure A.29. Modulus of Elasticity 29.

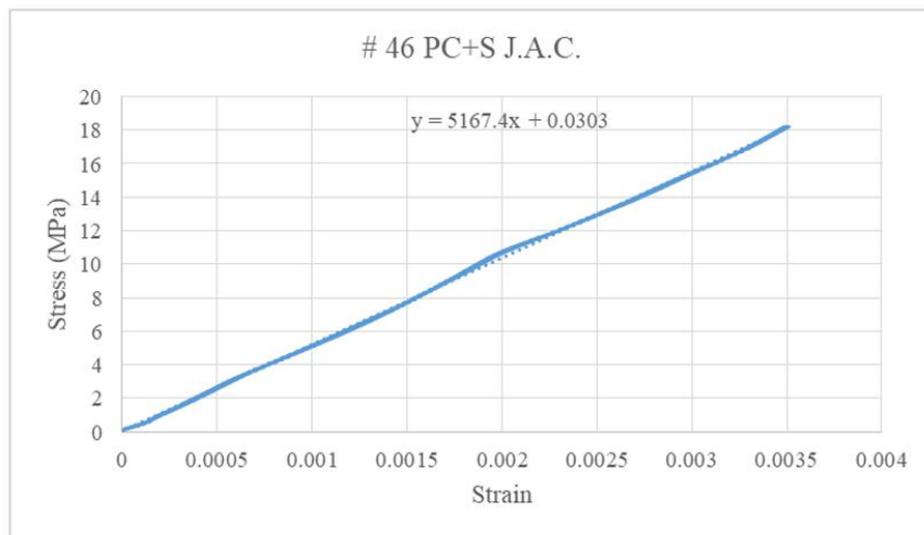


Figure A.30. Modulus of Elasticity 30.

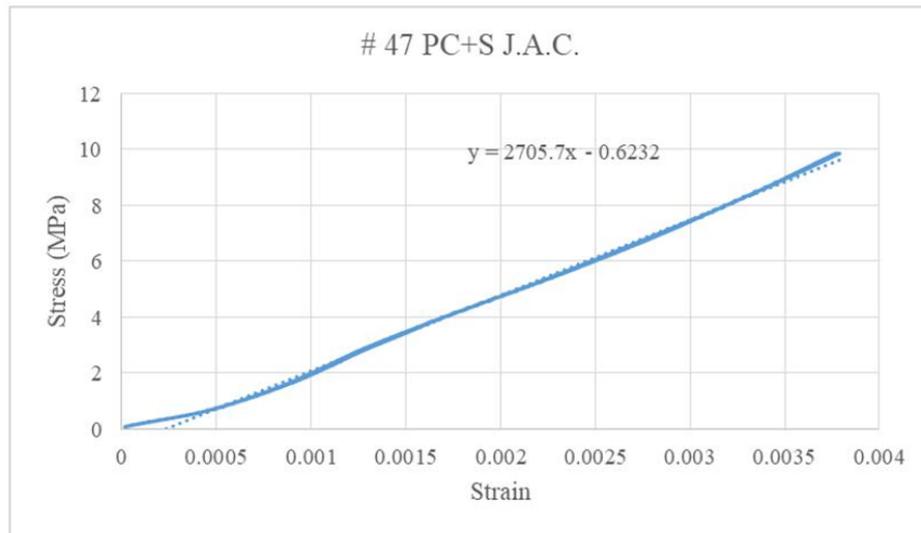


Figure A.31. Modulus of Elasticity 31.

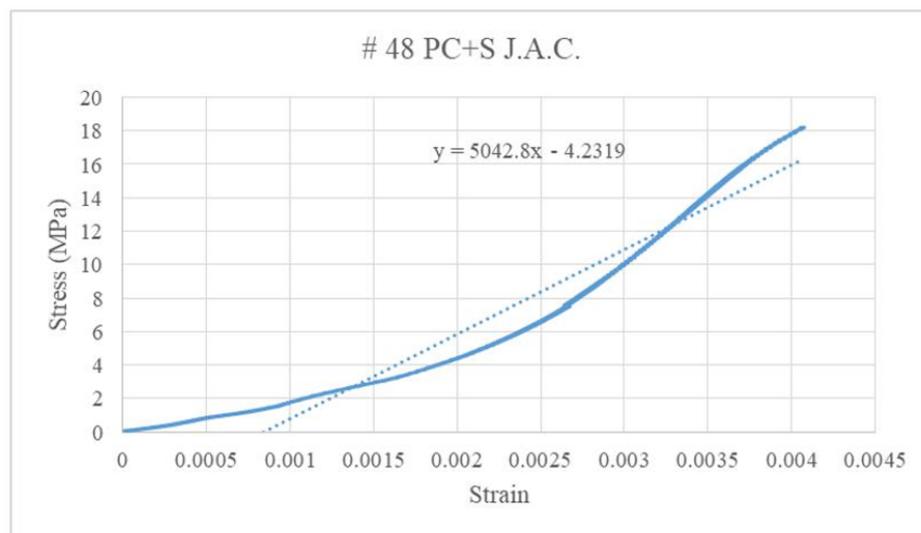


Figure A.32. Modulus of Elasticity 32.

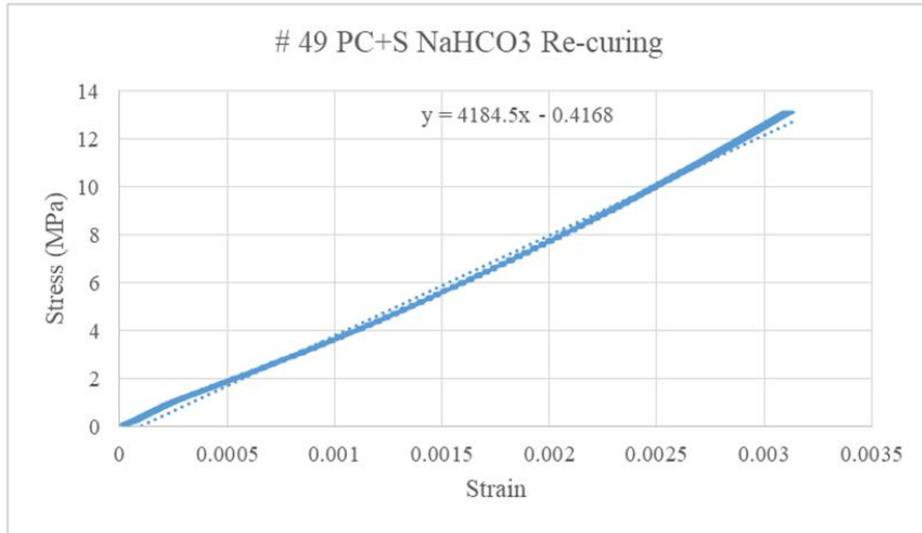


Figure A.33. Modulus of Elasticity 33.

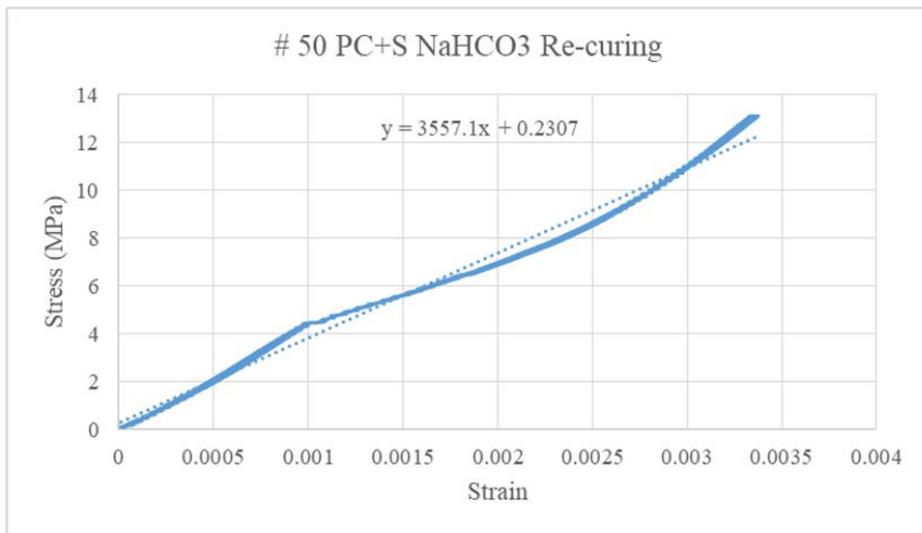


Figure A.34. Modulus of Elasticity 34.

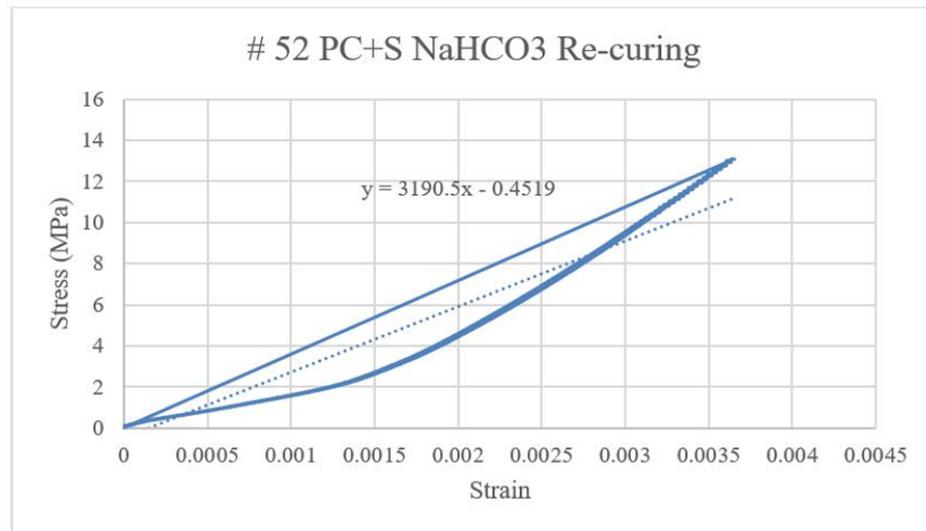


Figure A.35. Modulus of Elasticity 35.

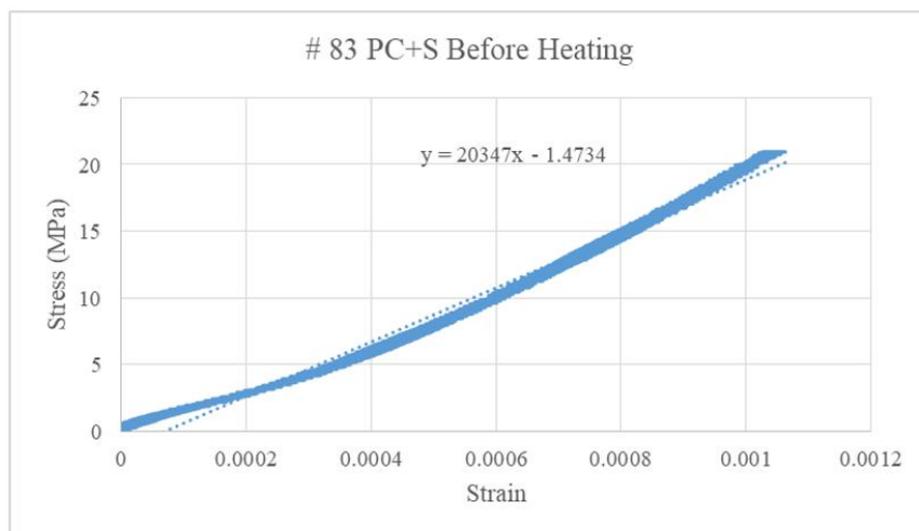


Figure A.36. Modulus of Elasticity 36.

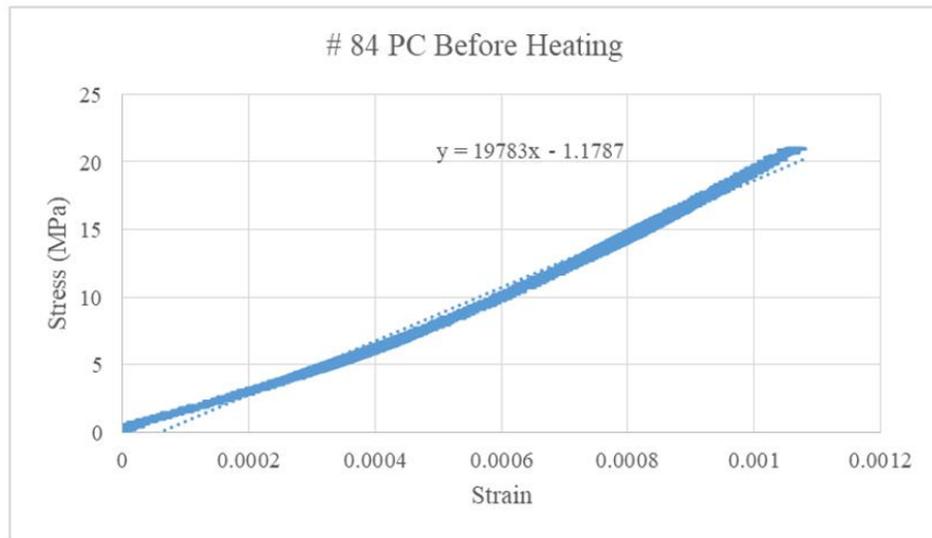


Figure A.37. Modulus of Elasticity 37.

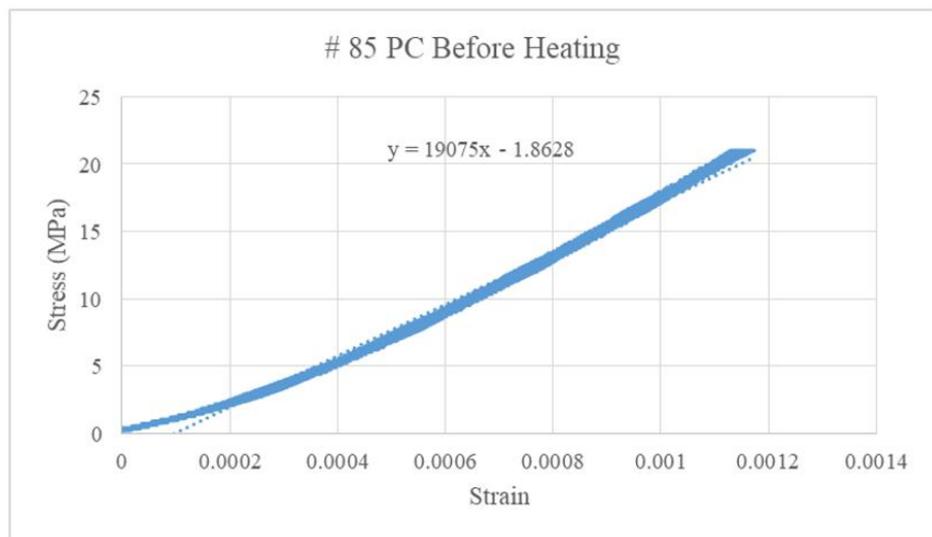


Figure A.38. Modulus of Elasticity 38.

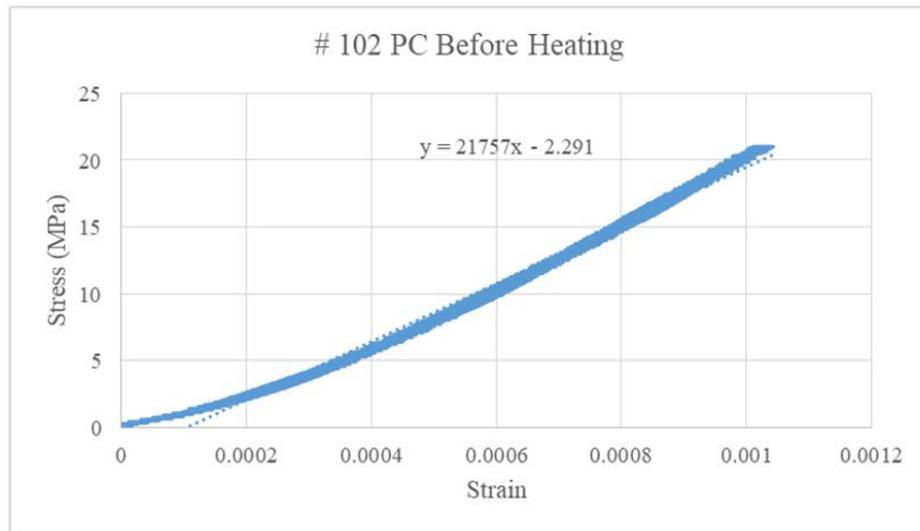


Figure A.39. Modulus of Elasticity 39.

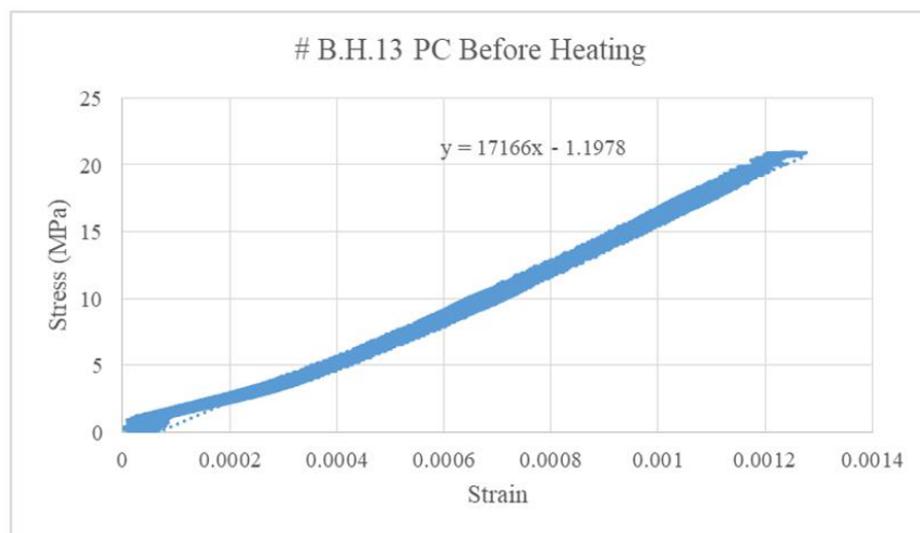


Figure A.40. Modulus of Elasticity 40.

APPENDIX B: AVERAGE RESIDUAL COMPRESSIVE STRENGTH OF ALL SAMPLES

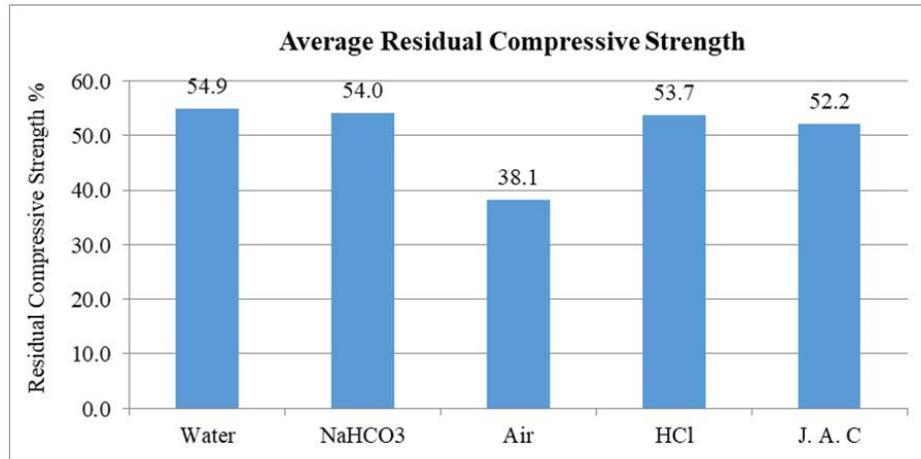


Figure B.1. Average residual Compressive strength of all samples.

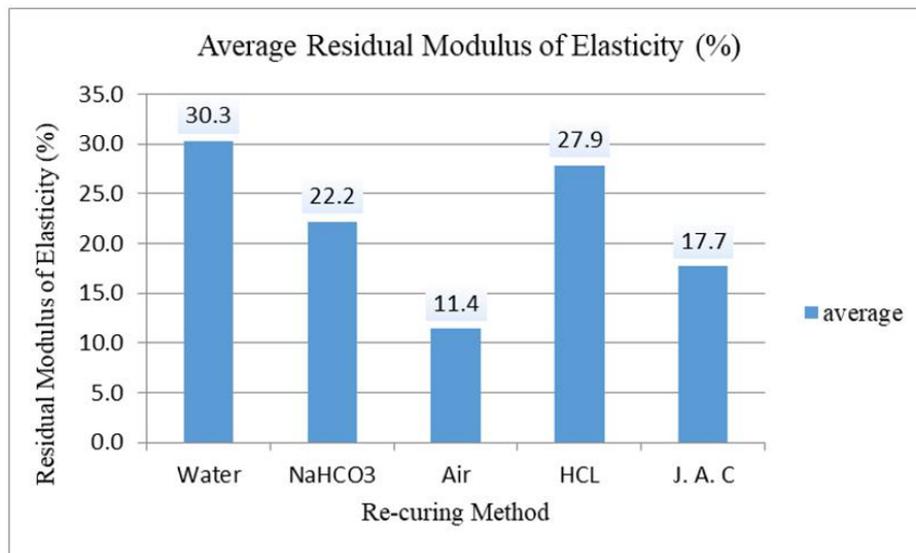


Figure B.2. Average Residual Modulus of Elasticity % of all samples.