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Sustainable high strength polymer concrete with high ratios of recycled aggregate from different decades under heat curing

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ABSTRACT

This study investigates the influence of heat curing on polymer concrete (PC) incorporating high replacement ratios (up to 80%) of recycled aggregates sourced from demolished buildings of different ages to prepare recycle aggregate polymer concrete (RAPC). The research addresses the gap in understanding how recycled aggregate properties, influenced by the age of source structures, impact PC performance under varying curing conditions. Two curing methods were applied: (1) air curing for 28 days and (2) accelerated heat curing at 100°C for 2 hours, followed by air curing. Results show that heat curing significantly enhances compressive strength, reaching 69 MPa in reference specimens compared to 53 MPa under air curing. When using 10-year-old recycled aggregates, RAPC maintained comparable strength (up to 65 MPa at 60% replacement), while 20-year-old recycled aggregates led to lower strengths (51 MPa at 60% replacement). The key contribution of this study lies in demonstrating that heat curing can compensate for strength loss in RAPC, enabling high replacement ratios while maintaining mechanical performance, knowing that the optimal balance between strength retention and sustainability was achieved at 60% replacement. Also, these findings underscore the potential of promoting sustainability by reducing natural resource consumption and construction waste.

Keywords: Polymer Concrete; Recycled Aggregate; Heat Curing; Sustainability; Mechanical Properties.

1. INTRODUCTION

Concrete is considered a vital material in construction and buildings. Traditional concrete has many favourable characteristics such as abundance in many countries and low-cost materials [1]. However, it also has considerable limitations such as its lower tensile and flexural strengths, reduced freeze-thaw cycling resistance and is easily affected by aggressive solutions [2]. In addition, due to the extensive use of concrete, the building industry is widely recognized as a prominent contributor to greenhouse gas emissions [3–5]. Particularly, the production and extraction of concrete's basic materials contribute to its harmful effects. For instance, carbon emissions from the production of cement pose a hazard to the environment and human health [6–8]. Therefore, it is vital to use new construction materials or the utilization of waste materials within the concrete industry and use environmentally friendly building techniques to lessen climate change, achieve goal number 13 outlined in the Sustainable Development Goals (SDGs) – 2030, and come by the target outlined in Paris Climate Accords – 2016 [9, 10].

Therefore, numerous studies have been executed to examine new types of construction and repair materials. One of these composites is Polymer Concrete (PC), which appeared around the end of the 1950s and rose to prominence in the 1970s for its usage in precast components, thin floor overlays, and repairs. PC has shown employment in particularly specialized sectors due to its characteristics including high compressive strength, quick curing, resistance to chemical attacks and high specific strength [11]. In 1971, it became clear that investigating PC materials was important with the setting up of the American Concrete Institute Committee

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548—Polymers in Concrete [12]. PC is a particulate composite material that was produced by polymer resin polymerization and also it does not comprise any hydrated cement [13]. The resin binds the aggregates together to form the concrete. Earlier usage of PC was limited to the cladding of buildings, then due to its rapid setting times, the ability to withstand corrosive environments, freeze-thaw resistance and high adhesion with the aggregates and reinforcement steel, it was used in various construction applications [14, 15], and is considered lighter than ordinary concrete [16, 17].

The variety of PC properties significantly depends on the preparation methods. Therefore, the properties are determined by the binders' type, size and distribution of aggregate, including curing process. Generally, epoxy resins, unsaturated polyester resins, furan resins, methyl methacrylate and polyurethane resins are considered as the most used resins in preparing PC [18, 19]. Epoxy resins are preferred over polyester and vinyl-ester resins due to their superior mechanical and resistance to humidity, thermal properties, low shrinkage, and high elongation, which generate a durable and flexible polymer matrix [20, 21]. To reduce the price of epoxy resins, a variety of additives can be added to dilute the resin's concentration [22]. The aggregates' particle size significantly affects the mechanical behaviour of the PC and enhances its physical and mechanical properties [23, 24]. Unsaturated polyester resin is widely used in PC preparation because it possesses good mechanical properties, affordability and availability [25]. Surface treatment with nano-hydrophobic coatings is one of the techniques used to improve the durability of construction materials and reduce moisture absorption [26]. Similarly, the application of thermal curing in recycled aggregate polymer concrete (RAPC) plays a similar role by enhancing compressive strength and reducing water absorption, ensuring the long-term performance of sustainable concrete.

From another perspective, aggregate is considered to be a vital component in concrete manufacture, representing 60–80% of the overall volume within the mix. Natural or waste aggregates based on kiln slag, fly ash, building materials wastes, and demolished buildings can be suitably used. Aggregate produced through concrete recycling is majorly composed of original aggregate bonded with cement mortar, suitable for reuse; while the remaining small proportion is composed of hardened cement mortar, which is not suitable for use in concrete. The cost of crushing concrete demolition waste is the main factor in determining the possibility of its recycling, as well as considering its granular gradation and controlling the separation of dust and unwanted components [27]. Recently, global environmental consciousness has grown, and reusing or recycling construction and demolition (C&D) wastes has emerged as one of the sustainable development goals along with a considerable positive influence on the environment, economy and society. CO_2 pollution and the use of nonrenewable energy can be cut by 62% and 58%, respectively [28]. Recycling has become a policy that many industrialized countries have embraced and enforced. New Zealand and Denmark are considered as the pioneers in this regard [29]. Also, many minerals can be used as aggregate replacements in the production of cementitious composites [30, 31].

Various researchers have discussed on recycling aggregate and PC and its properties. In 2021, TOBEIA *et al*. [32] used admixtures of styrene butadiene-rubber and polypropylene fiber to enhance the compressive and tensile strengths of concrete infused with recycled aggregate. It was discovered that using styrene butadiene rubber improves both the compressive and splitting tensile strengths by strengthened bond between the recycled aggregates, while the inclusion of polypropylene fiber doesn't lead to a substantial gain in compressive strength. On the contrary, there was an improvement in splitting strength. In 2020, SECO *et al*. [33] studied on suitability comparison of metallurgical wastes and natural aggregates for preparing polyester PC (PPC). The results showed that ladle slag specimens demonstrated the best compressive and flexural strengths, while alumina filler specimens displayed the highest losses in compressive and flexural strengths due to freeze-thaw cycles. Also in 2020, KIRUTHIKA *et al*. [34] improved PC mix by utilizing isophthalic resin for frames and inspection covers manufacturing. This improved PC possesses many favourable characteristics such as high mechanical properties, high durability and good acids resistance.

As a result of the destruction of some governorates in Iraq and the large number of destroyed buildings and the difficulty of disposing of them, this study was executed to utilize the building waste as recycled coarse aggregate in PC production and compare its mechanical and physical properties through heat and air curing methods. The primary purpose of this investigation is to include ecological and sustainable concepts into the design of PC mixes by partially replacing coarse aggregates with recycled aggregates. Recycling is encouraged, cost savings are possible, and non-renewable resources are preserved when recycled aggregates are substituted for normal aggregates in the production of concrete.

Construction and Demolition (C&D) waste is a sort of materials that is generated from construction and not involved in solid waste of municipality. Different types of materials are included in C&D waste such as concrete and its components and asphalt concrete (asphalt pavement). These types of waste materials are utilized in the construction of buildings, roads, bridges, ports, road tunnels and other structures. Currently, the

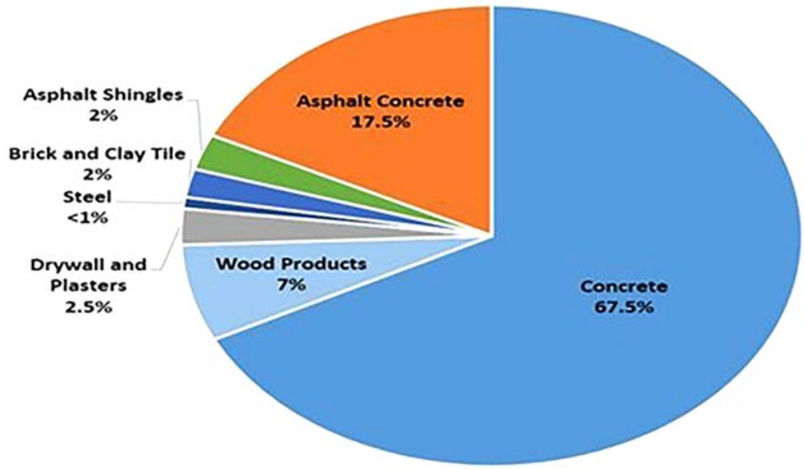

Figure 1: Composition of construction and demolition waste (before processing), 2018 with 600 million tons.

C&D debris amounts generation estimate represents from building, road, and bridge construction, rehabilitation, and demolition activities, among other structural activities. Based on a report published by the Turkish Chamber of Environmental Engineers, 104 million tons of construction waste was generated due to February 2023 earthquake [35]. In 2018, the United States produced a total of 600 million tons of construction and demolition waste. Figure 1 displays the C&D waste generation for 2018, considering that concrete C&D accounted for the majority (67.5%) [36].

Figure 2 displays the 2018 C&D waste that was recycled or disposed of in landfills. At 52%, aggregate was the primary EOL next use for C&D waste. About 313 million tons of C&D garbage in total were delivered to be aggregated. About 301 million tons of concrete alone were delivered to be aggregated. At 24% of the total volume of C&D trash, landfill was the next-largest end destination. Around 144 million tons of C&D waste were dumped in landfills as a whole. Concrete alone accounted for around 71 million tons that was dumped.

The greatest waste stream in the EU is made up of C&D waste, which is produced over time in relatively constant amounts and recovers quickly. This may imply that the construction industry is fairly circular, however a closer look at waste management procedures reveals that C&D waste recovery is primarily focused on backfilling operations and low-grade recovery, including the use of recycled aggregates in road sub-bases. Actually, upon further analysis of the data, it becomes evident that the significant recovery of construction and demolition (C&D) waste is mostly attributed to backfilling (see Figure 3) or the utilization of recycled aggregates derived from the mineral component of C&D waste for purposes such as road sub-bases. Figure 4 depicts the C&D waste treatment (% of treated waste) in 2016 for European nations [37].

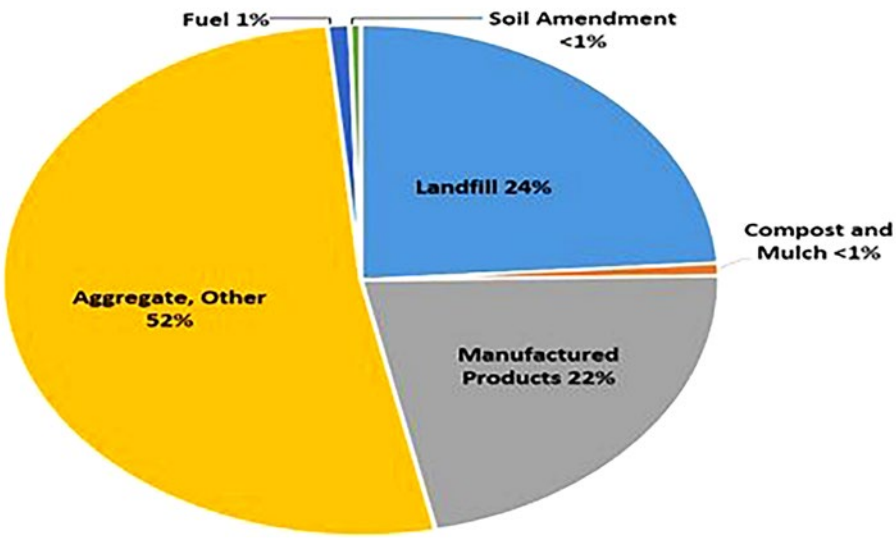

Figure 2: Construction and demolition waste management by destination, 2018 with 600 million tons.

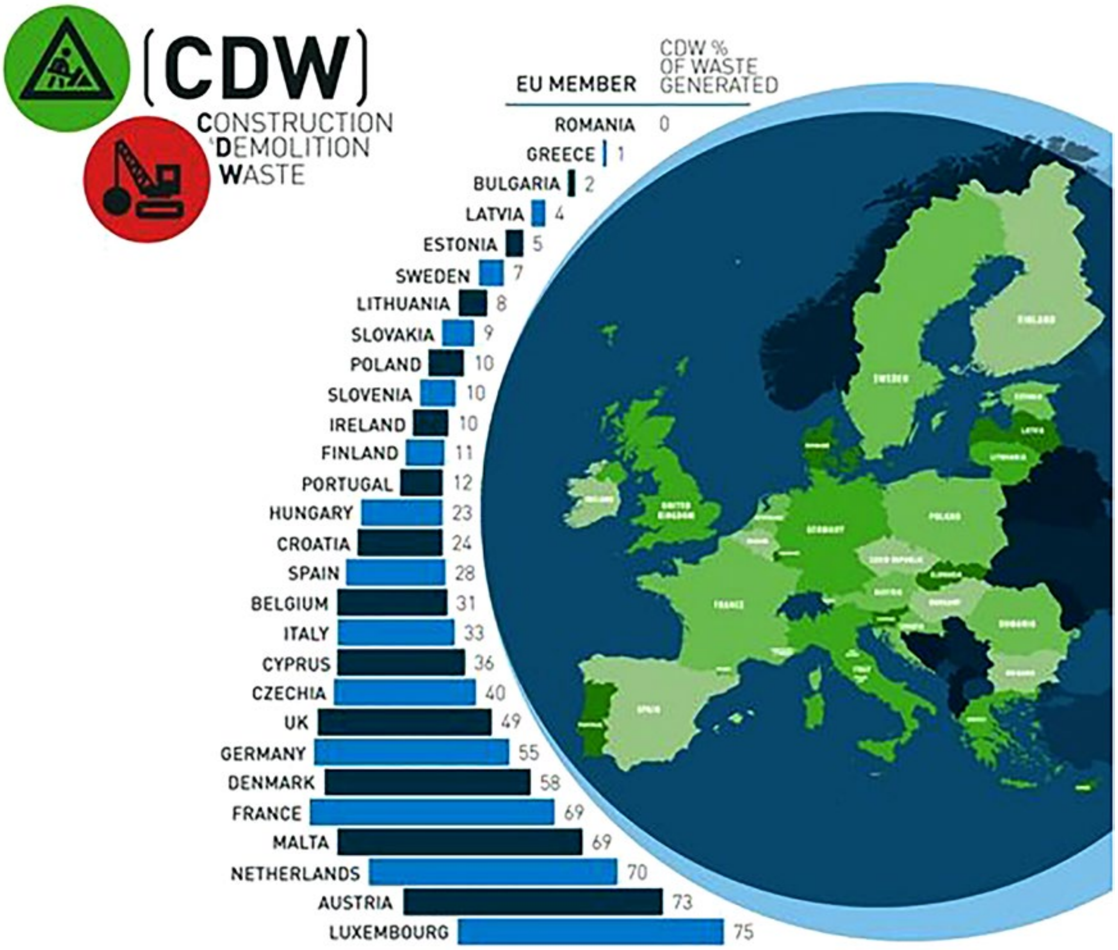

Figure 3: The percentage of CDW to the total volume of waste generated in Europe countries, 2019 [38].

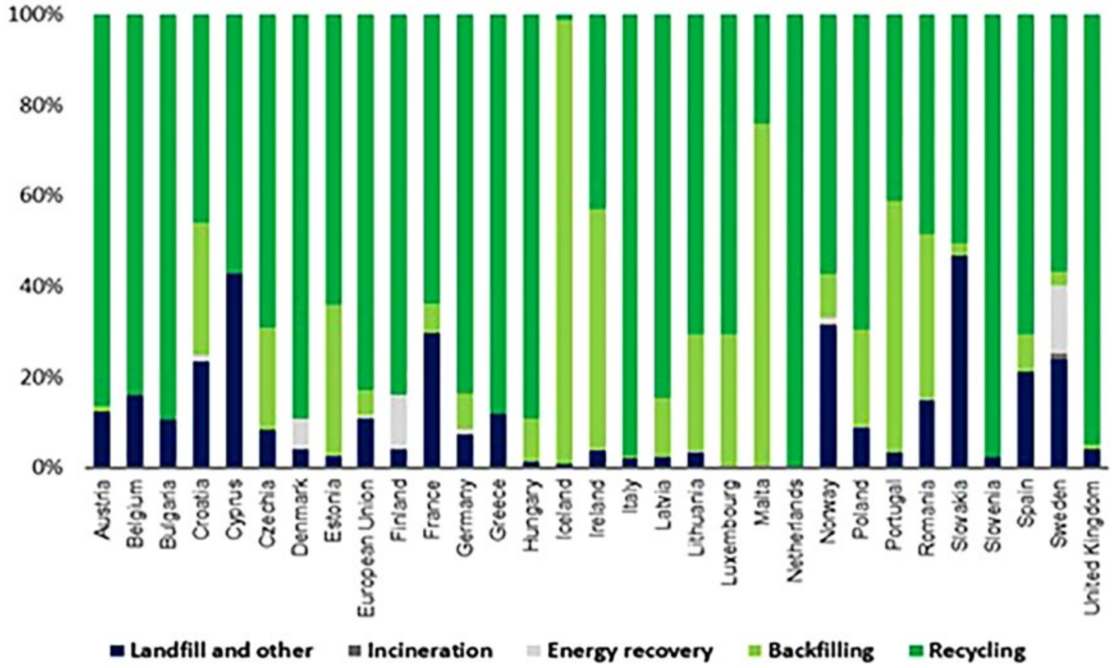

Figure 4: C&DW rates of recycling, energy recovery and landfilling in 2016.

The biggest single activity in the EU for producing garbage is CDW, at 36%. Now consider that some of the products produced in these nations, such as metals, glass, wood, and concrete, have significant resource values. Bricks and concrete from demolished buildings can be reused to create environmentally friendly road surfaces. Asphalt that has been crushed and reconstituted can be used again. Lumber and chipboard can be made from untreated wood. Germany is known for recycling a substantial amount of construction and demolition waste (CDW), specifically 68 million tonnes each year. However, it is the Netherlands that stands out in Europe for its impressive recycling rate, as it successfully recycles 90% of its CDW. There are considerably more that can be accomplished, which is why the Waste Framework Directive 2008/98/EC established a target of non-hazardous CDW being recycled and reused at a rate of 70% (by weight) by 2020 [38].

The demand for sustainable construction materials has increased the focus on incorporating recycled aggregates. However, high replacement ratios can weaken mechanical properties and limiting their practical use. This study investigates heat curing as a method to enhance the strength and durability of RAPC, providing an eco-friendly alternative to natural aggregates. The research evaluates key properties through compressive strength, splitting tensile strength, Schmidt hammer, ultrasonic pulse velocity, and water absorption tests. These findings contribute to reduce reliance on natural resources, and promoting sustainable waste management in construction.

2. MATERIALS AND METHODS

2.1. Used materials

This study utilized carefully selected materials to ensure the optimal performance of RAPC. The primary components include unsaturated polyester resin as a binder, fine and coarse aggregates sourced from natural and recycled materials, and a hardener to initiate the polymerization process. The recycled aggregates were obtained from demolished buildings of different ages (10 and 20 years) to assess the influence of aggregate age on mechanical properties. The properties of each material are detailed in the following subsections.

2.1.1. Unsaturated polyester resin

Unsaturated polyester resin is widely used in polymer concrete due to its high adhesion, durability, and chemical resistance. It acts as the primary binder, replacing traditional cement and enhancing the composite's mechanical performance. One of its key contributions is improving compressive strength by creating a dense polymer matrix that bonds effectively with aggregates. Because of their lower cost, unsaturated polyester resin is the most widely used polymer binders for PC. The specification of the used unsaturated polyester resin is as shown in Table 1. The unsaturated groups of the polyester resin and the monomer react during hardening and the resulting polymer binder is thermosetting polymer.

2.1.2. Fine aggregate

In addition, Al- Ekhaider sand with a maximum size of 4.75 mm was used. The percentage of sulfate and the grading of fine aggregate are both in accordance with the requirements of the Iraqi specification (IQS No. 45/1988). The chemical and physical properties of natural sand are illustrated in Table 2.

Table 1: Properties of the unsaturated polyester resin according to the manufacturer.

COLOUR	CLEAR YELLOWISH
Shape and appearance	Liquid
Solid in aqueous solution	57–63%
Viscosity at 25º C	200–300 cps

Table 2: Characteristics of fine aggregate used throughout this work.

PHYSICAL PROPERTIES	TEST RESULTS	LIMITS OF IRAQI SPECIFICATION
Specific gravity	2.63	–
Bulk density (kg/m^3)	1592	–
Sulfate content %	0.3	–
Absorption %	0.4	≤ 0.5 %

Table 3: Characteristics of the coarse aggregate employed in this experiment.

PHYSICAL PROPERTIES	TEST RESULTS	LIMITS OF IRAQI SPECIFICATION
Specific gravity	2.64	–
Bulk density (kg/m^3)	1560	–
Sulfate content %	0.096	≤ 0.1 %
Absorption %	0.7	–

Figure 5: Crushing process of the recycle aggregate.

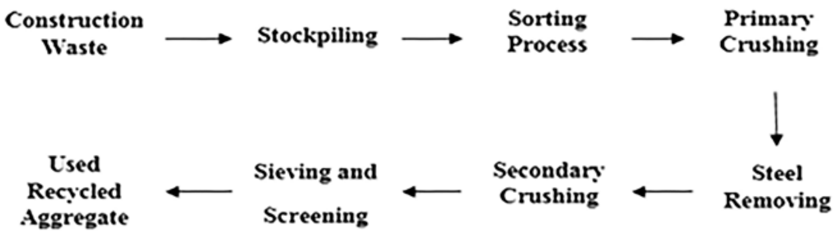

Figure 6: Preparation process of the used recycled aggregate.

Table 4: The properties of the recycled aggregate.

PROPERTIES	10 YEARS	20 YEARS
Saturated surface dry (SSD) specific weight	2.61	2.49
Absorption rate %	2.32	5.5
Bulk density, compacted kg/m^3	1300	1270
Los Angelos abrasion %	25.8	30.3

2.1.3. Coarse aggregate

Crushed gravel of 20 mm maximum size from Al-Nebaai region was used as coarse aggregate. The sulfate content and coarse aggregate grading are both in accordance with the requirements of the Iraqi specification (IQS No. 45/1988). The chemical and physical properties of natural sand are depicted in Table 3.

2.1.4. Recycled Coarse Aggregate (RCA)

The recycled aggregate was obtained from two buildings under demolition of different ages (10 and 20 years). Large chunks of crushed concrete were transported to the lab and further broken down using a jaw crusher machine into pieces smaller than 37.5 mm to conform to the requirements of the Iraqi specification (IQS No. 45/1988) as shown in Figure 5, also the preparation process of the recycled aggregate is shown in Figure 6. The properties and gradation of recycled aggregate are shown in Table 4 and Figure 7, respectively.

The elemental composition of the specimens for different ages (10 and 20 years) are examined by EDX test and are shown in Table 5 and Figures 8 and 9, respectively.

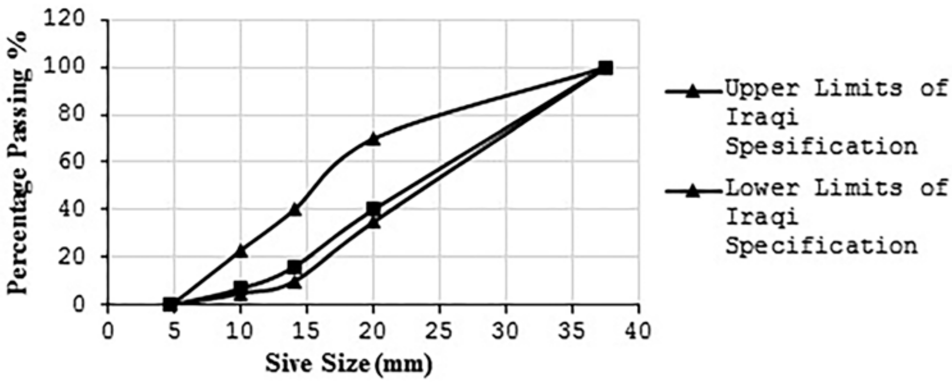

Figure 7: Grading curve of recycled aggregate.

Table 5: The elemental composition of the recycled aggregate.

ELEMENTS	10 YEARS		20 YEARS	
	Wt. %	σ	Wt. %	σ
Ca	100	0.0	20.9	1.1
O	–	–	60.2	1.7
Si	–	–	14.2	0.9
Al	–	–	3.7	0.5

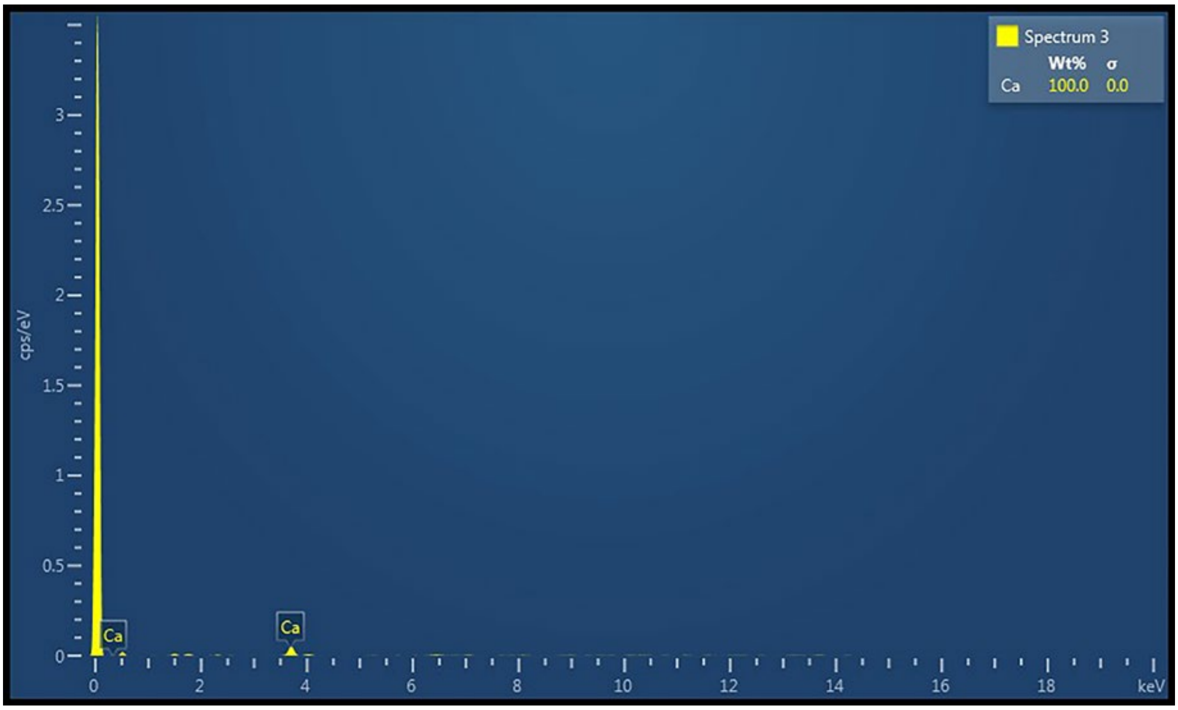

Figure 8: Specimen's composition from 10 years buildings.

2.2. Specimens preparation and curing

Different percentages of recycled aggregate (20%, 40%, 60%, and 80%) were utilized to partially replace the natural coarse aggregate to produce RAPC and the results are compared with reference concrete (without recycled aggregate). The study performed coarse aggregate replacement was conducted using a weight-to-weight approach to maintain consistency in the total mix weight, which is particularly relevant in polymer-based composites where the polymer-to-aggregate ratio plays a critical role in performance. Unlike water-based

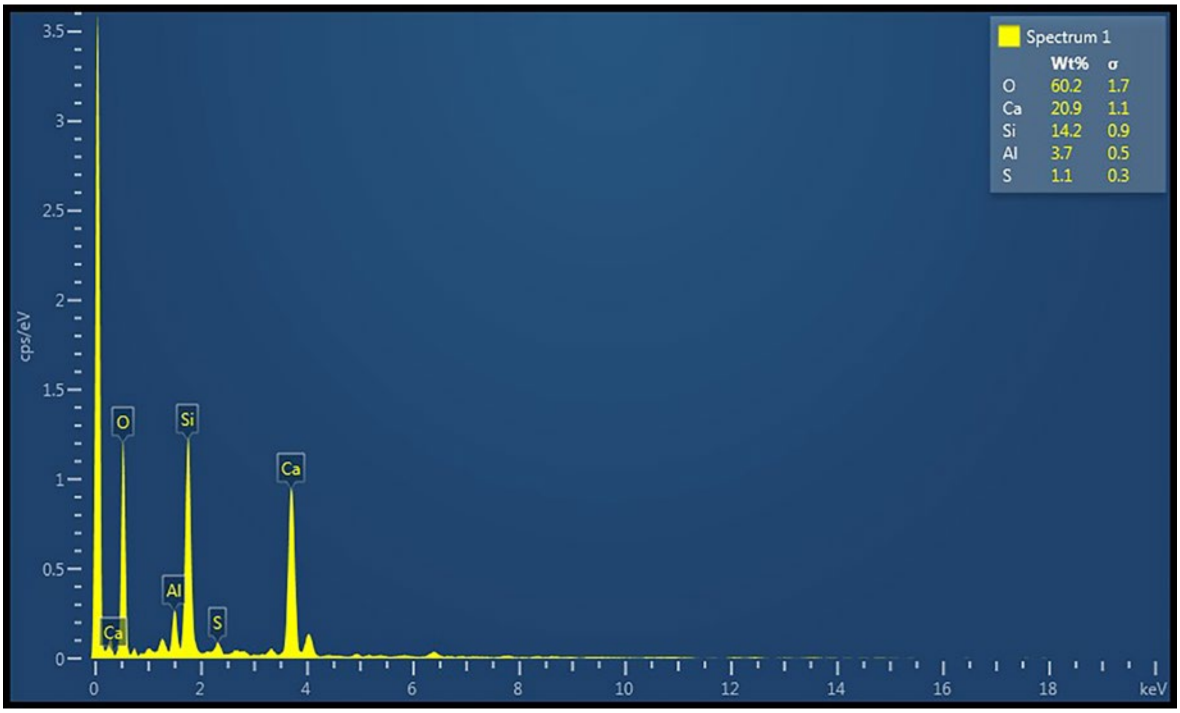

Figure 9: Specimen's composition from 20 years buildings.

Table 6: Mixture details in kg/m^3.

SYMBOL	POLYESTER	FINE AGGREGATE	COARSE AGGREGATE	RECYCLED AGGREGATE 10 YEARS	RECYCLED AGGREGATE 20 YEARS
REF	400	600	800	–	–
RA1	400	600	640	160 (20%)	–
RA2	400	600	480	320 (40%)	–
RA3	400	600	320	480 (60%)	–
RA4	400	600	160	640 (80%)	–
RA5	400	600	640	–	160 (20%)
RA6	400	600	480	–	320 (40%)
RA7	400	600	320	–	480 (60%)
RA8	400	600	160	–	640 (80%)

cementitious systems, polymer concrete does not rely on water-cement ratios or hydration reactions. Fine and coarse aggregates were mixed for three minutes. Unsaturated polyester resin was mixed with hardener in 0.01% of its weight and combined into the existing mix before being poured in three stages into the moulds. For air curing, the specimens were demoulded after 24 hours and left to air cure, while for heat curing, an hour after casting, the moulds were placed in an oven to cure at 100°C for 2 hours and then also left to cure in the air. The specimens were taken out of the moulds after 24 hours. The air curing was carried out at room temperature for 28 days. The details of the constituents used in the mixture are shown in Table 6.

3. TEST PROCEDURE

3.1. Compressive and splitting tensile strength

The compressive strength test was conducted in compliance with [39]. A 2000 KN capacity electrical testing machine was used to perform this test on the 100 mm * 100 mm * 100 mm cubic specimens. The test was carried

Figure 10: Splitting tensile test at the right and compressive test at the left.

out after 28 days of heat and air curing. The splitting tensile strength test was conducted in compliance with the [40]. The same test machine was used, but a cylindrical specimens with 100 mm * 200 mm were positioned on its horizontal axis. The test was carried out after being exposed to heat and air for a period of 28 days. Figure 10 depicts the experimental setup for testing the compressive and splitting tensile strengths of specimens.

3.2. Schmidt hammer

The test was conducted in compliance with the [41]. Cubic specimens (100 mm in dimension) were used in this test. The Schmidt hammer type N was used to assess the compressive strength of concrete as shown in Figure 11. The basic idea of this test is to determine how quickly an elastic mass rebounds after colliding with the surface of concrete. The number of rebounds is determined by concrete hardness and the amount of energy consumed after the collision. The concrete specimen that will be examined should be smoothened and cleaned. When the hammer rebounded from the plunger after being slammed on the concrete, the mass provided the scale with a reading. This value is known as the rebound number, and it is determined by the amount of energy contained in the spring as well as the mass' sizes.

3.3. Ultra-sonic pulse velocity

The test was conducted in compliance with the [42]. Cubic specimens (100 mm in dimension) were used in this test. First, the specimen's faces and transducers were greased to remove any entrapped air between the transducer and the specimen surfaces as shown in Figure 12. The transducers' faces were then placed against the test specimen sides, and the average time duration was determined by shifting the transducers. The transducer frequency used was 54 KHz with 3500 m/c pulse velocity.

Figure 11: Schmidt hammer apparatus used in the work.

Figure 12: Ultrasonic pulse velocity apparatus used in the work.

3.4. Total absorption

Cubic specimens were used to measure the absorption test in compliance with [43]. The specimens were removed and weighed after a 24-hour drying period between 100 and 110°C. After that, the specimens were put into petroleum products and left there for 48 hours. Then, the specimens were taken out and let to dry before they were weighed again.

4. RESULTS AND DISCUSSION

4.1. Compressive strength

Figures 13 and 14 depict the compressive strength values for cubic specimens with different recycled aggregate for both air and heat curing, respectively. The results of compressive strength for (RAPC) specimens under air curing without any replacement show 53 MPa, while it shows a continuous decrease with increasing the recycled aggregate 10 years reaching 39 MPa with 80% replacement. For the 20 years recycled aggregate, results show a higher decreasing behaviour with increasing the replacement ratio reaching 32 Mpa, afreed with [44]. The results of compressive strength for (RAPC) specimens under heat curing without any replacement show 69 MPa, which possess higher values in comparison to the air curing values which show a slight decrease with increasing recycled aggregate 10 years until 60% showing 65 MPa but then dropped to 54 MPa with 80% of aggregate replacement. For the 20 years recycled aggregate, there was a finding that, the strength values keep decreasing to reach 43 MPa with 80% of aggregate replacement. These results indicate that heat curing causes more strength gaining than air curing, and that is due to the accelerated polymerization process which causes high hardening and also due to good compacting and high dispersion of polymer particles in the aggregate, while the behaviour of strength decreasing occurred due to the porous old mortar adhering to the surface of the 20 years recycled aggregate, which caused to absorb moisture faster when mixing the components compared to natural aggregates. This behaviour which makes the 10 years recycled aggregate gives higher strength than 20 years and can be used as aggregate replacement up to 60% with a very slight decreasing in the compressive strength [45].

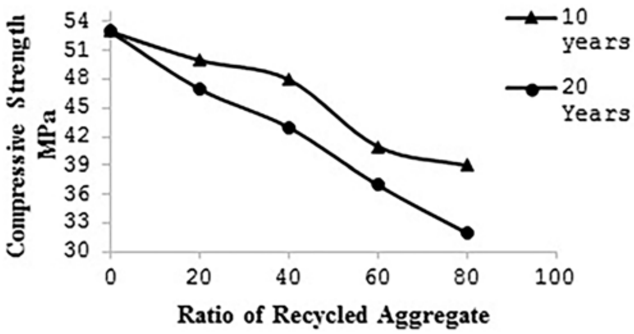

Figure 13: Compressive strength results for RAPC specimens with different recycled aggregate ratios under air curing.

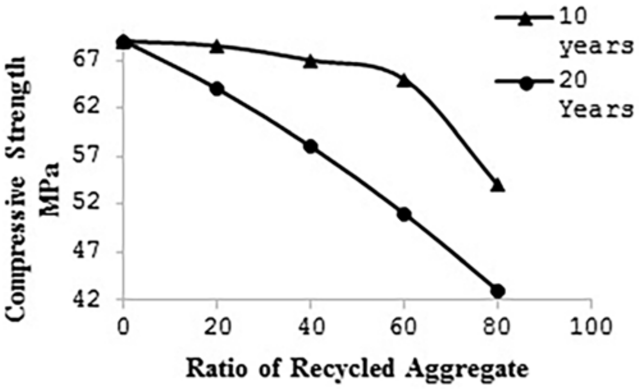

Figure 14: Compressive strength results for RAPC specimens with different recycled aggregate ratios under heat curing.

4.2. Splitting tensile strength

Existing cracks, especially those connected to the interfacial transition zone, govern tensile load failure in concrete, therefore, splitting tensile strength is considered to be a very important characteristic [46]. Figures 15 and 16 show the splitting tensile strength values for cylindrical specimens with different recycled aggregate for both air and heat curing, respectively. The results of splitting tensile strength for RAPC specimens under air curing without any replacement show 7.2 MPa, while it shows a continuous decrease with increasing the recycled aggregate 10 years reaching 3.8 MPa with 80% replacement. For the 20 years recycled aggregate, results show a higher decreasing behaviour with increasing the replacement ratio reaching 3.1 Mpa, agreed with [47]. As in the compressive strength behaviour, the results of splitting tensile strength for RAPC specimens under heat curing without any replacement show 11.4 MPa, which show higher values in comparison to the air curing values showing a slight decrease with increasing recycled aggregate 10 years until 60% reaching 10.3 MPa but then it dropped to 8 MPa with 80% of aggregate replacement. For the 20 years recycled aggregate, it was observed that, the strength values show a continuous decrease reaching 5.3 MPa with 80% of aggregate replacement. This behaviour occurred due to the formation of a three-dimensional networks of polymer molecules within the concrete, which improves the bonding system, while the reduction in 20 years recycled aggregate occurred due

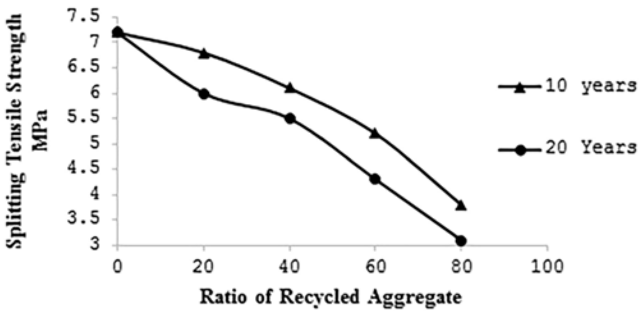

Figure 15: Splitting tensile strength results for RAPC specimens with different recycled aggregate ratios under air curing.

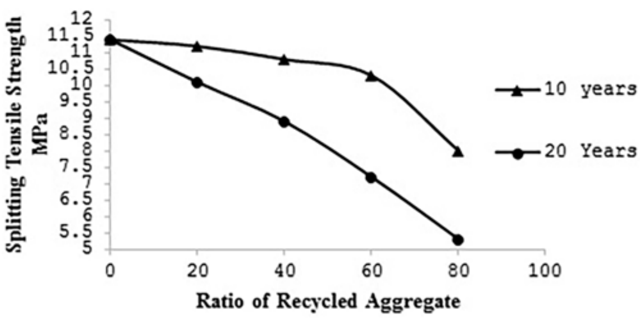

Figure 16: Splitting tensile strength results for RAPC specimens with different recycled aggregate ratios under heat curing.

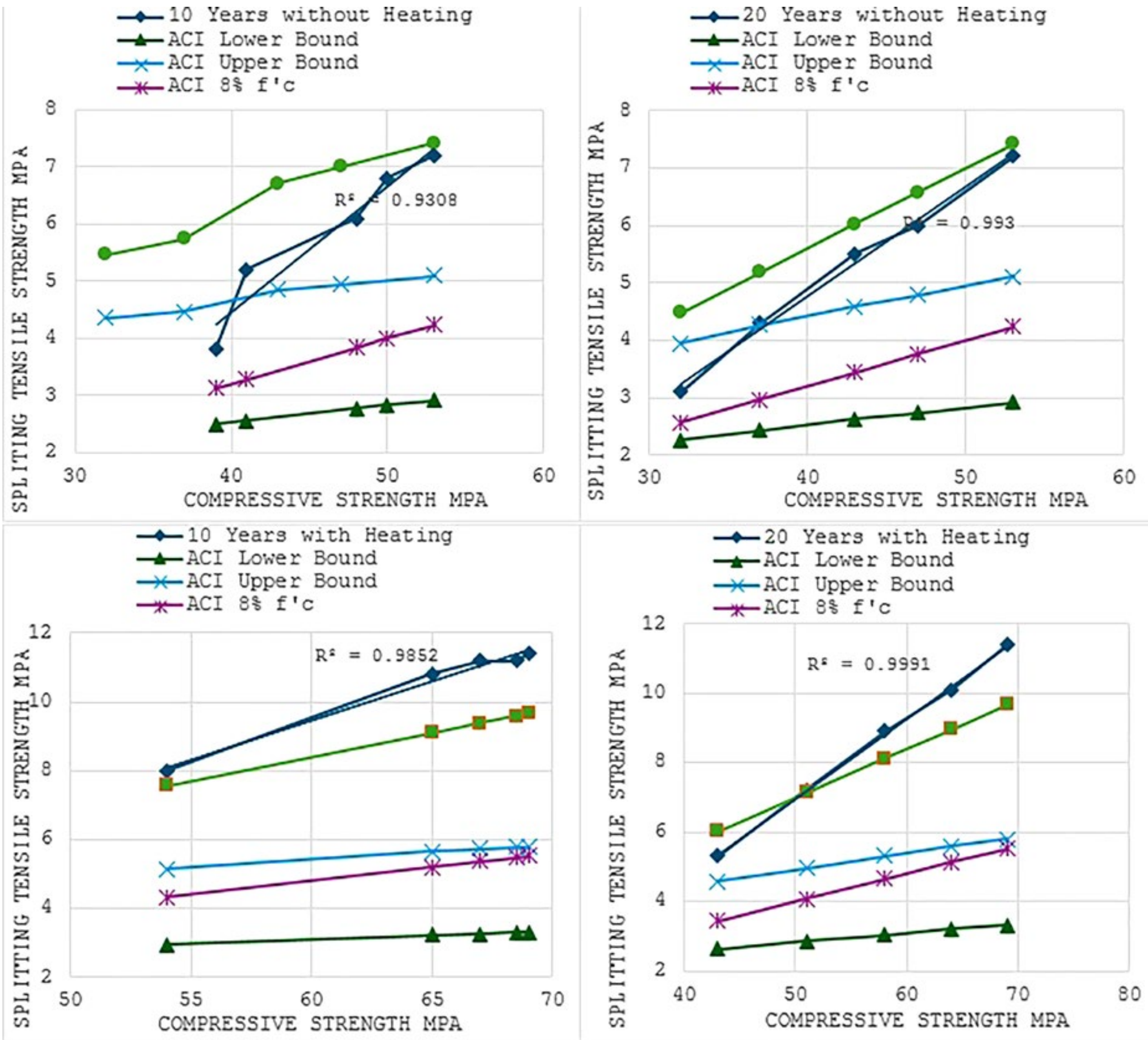

Figure 17: Analysis and comparison of tensile and compressive strength according to ACI 318-14 code equations RAPC specimens with different recycled aggregate ratios.

to the weakened spots that may have happened during demolition and also from the EDX test results, they indicated that many compositional transformations occurred in it, while the 10 years recycled aggregate maintains its original composition 100% Ca.

To form a relationship between compressive strength and splitting tensile strength of RAPC, experimental results were compared with the empirical ACI equations showing a linear relationship between these variables as illustrated in Figure 17. When the experimental results of splitting tensile strength were analyzed and compared with the standard equations given in ACI 318-14, it was found that the measured values exceeded the upper limit of the square root equation ($0.7\sqrt{f'c}$), indicating that the polymer matrix has improved mechanical properties that enhance the tensile strength compared to the conventional models adopted in the code. However, despite this superiority, the results showed that they are still within the acceptable range of 8% to 14% of the compressive strength, which means that the mechanical behavior of the studied concrete does not go beyond the structurally acceptable limits [48, 49].

4.3. Schmidt hammer

One of the most widely used non destructive test NDT methods for in situ strength assessment of concrete structures is rebound surface hardness testing. Concrete hardness testing methods are indirect methods used in measuring concrete strength. Concrete compressive strength is calculated by the calibrating relation between non-destructive test parameters and concrete strength. Figures 18 and 19 show the Schmidt values for cubic specimens with different recycled aggregates for both air and heat curing, respectively. The results of Schmidt

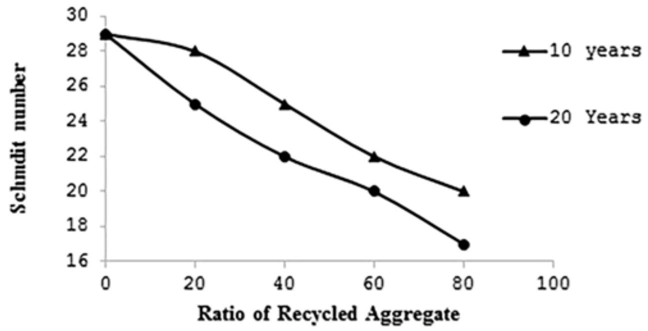

Figure 18: Schmidt hammer results for RAPC specimens with different recycled aggregate ratios under air curing.

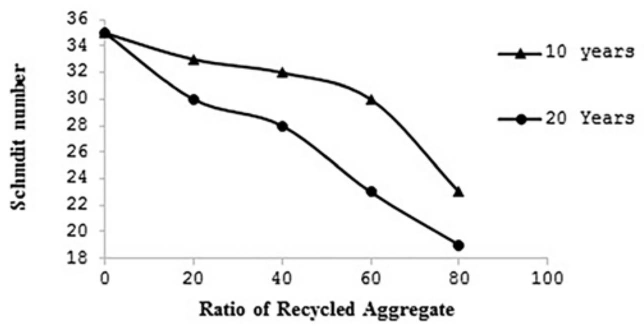

Figure 19: Schmidt hammer results for RAPC specimens with different recycled aggregate ratios under heat curing.

hammer test for RAPC specimens under air curing show a continuous decrement with increasing the recycled aggregate ratio 10 years reaching 20 MPa with 80 %. For the 20 years recycled aggregate, more decreasing are occurred with increasing the recycled aggregate replacement showing 17 MPa. The results of Schmidt test for RAPC specimens under heat curing show less decreasing values with recycled aggregate 10 years having 30 MPa with 60% but it shows higher dropping in the values and reaches 23 MPa with 80% in aggregate replacement. For recycled aggregate 20 years it was 30 MPa with 20% aggregate and beyond 40% it started to decrease greatly and reaches 19 MPa with 80% recycled aggregate. The results can be influenced by many factors; the characteristics of the mixture (age of aggregate), moisture condition, surface carbonation, time of hardening and curing type. Therefore, these factors must be considered during the Schmidt hammer test [50]. Also the results indicate that the rebound numbers increase faster under heat curing and this behaviour occurs due to the surface humidity which decreases with heating [51].

4.4. Ultra-Sonic Pulse Velocity (UPV)

Ultrasonic tests are employed within the field of structural engineering to evaluate the characteristics of materials, identify defects, and evaluate degradation. The condition of the material is evaluated by comparing field measurements to the reference property value. The amount of material degradation is determined by the ratio of field UPVs to the reference UPV. Figures 20 and 21 show the ultra-sonic pulse velocity results for cubic specimens with different recycled aggregate for both air and heat curing respectively. The results of UPV test for RAPC specimens under air curing show a similar behaviour which show a continuous decreasing with increasing the recycle aggregate ratio, with the recycled aggregate 10 years reach 4.1322 Km/sec at 80% of replacement and 4.0666 Km/sec with 20 years recycle aggregate under air curing. The results also show higher velocity values under heat curing which reach 5.4824 Km/sec and 5.3705 Km/sec for 10 and 20 years recycled aggregate respectively. The results indicated that the UPV values increase under heat curing since ultrasonic wave travels faster through solid materials than voids; this increase occurred as a result of the polymer network development, which influences the space ratio and induces a rise in the wave speed. As a result, the ultrasonic pulse velocity increases as the concrete mass within the same volume increases, also it concluded that this increment in velocity results from the high homogeneity and good mixing which causes increasing in the density and that means the waves need less time to pass through the specimens [52].

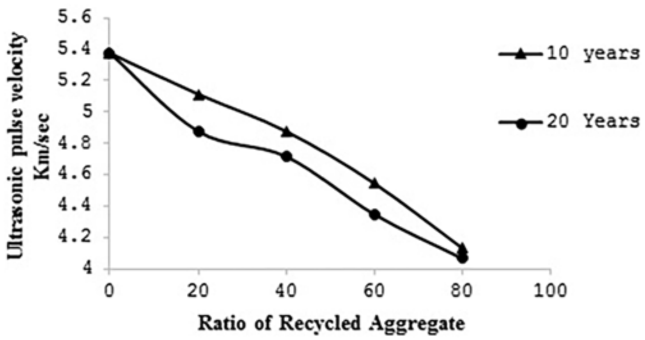

Figure 20: Ultra-sonic pulse velocity values for RAPC specimens with different recycled aggregate ratios under air curing.

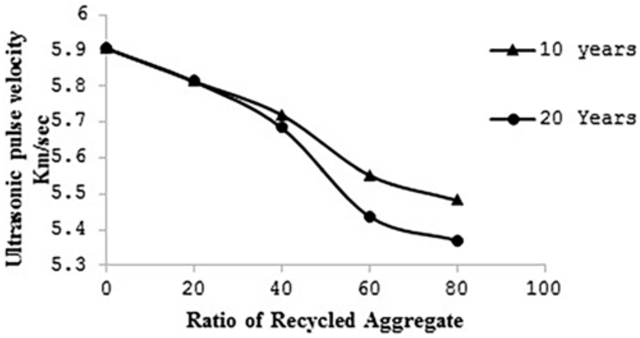

Figure 21: Ultra-sonic pulse velocity values for RAPC specimens with different recycled aggregate ratios under heat curing.

The ultrasonic pulse velocity (UPV) test is widely used to evaluate concrete quality based on wave propagation speed. Higher UPV values indicate greater material density and lower porosity, improving mechanical performance. According to standard references, concrete quality classifications based on UPV range from weak (< 3.0 km/s) to high (> 4.5 km/s) [53, 54]. In this study, UPV values ranged from 4.0666 km/s to 5.4824 km/s, indicating well to excellent quality across different recycled aggregate types and curing methods. The highest values were recorded for heat-cured RAPC with 10-year-old recycled aggregates (5.4824 km/s), demonstrating improved density and bonding due to accelerated polymerization. In contrast, air-cured RAPC with 20-year-old recycled aggregates exhibited the lowest UPV values (4.0666 km/s), attributed to higher porosity in the aged recycled material. These findings align with previous studies, confirming that recycled aggregates generally reduce UPV, but heat curing effectively compensates for this effect by enhancing matrix integrity.

4.5. Total absorption

Water absorption is a basic test for determining the durability of concrete [55]. Concrete's durability suffers as a consequence of increased water absorption. More water absorption resulted in freezing and thawing activity, which caused the concrete to deteriorate. According to previous research, increased water absorption of concrete

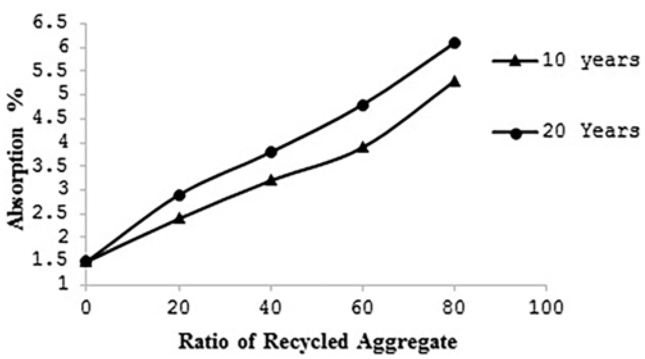

Figure 22: Absorption values for RAPC specimens with different recycled aggregate ratios under air curing.

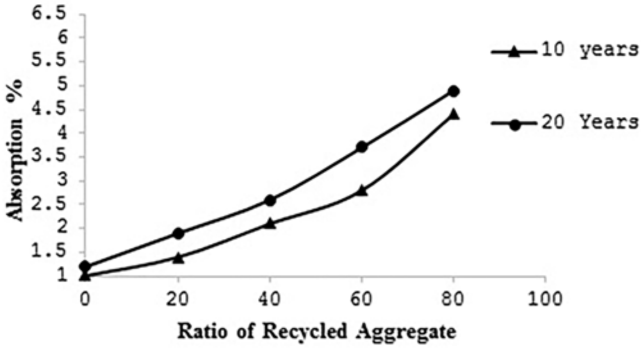

Figure 23: Absorption values for RAPC specimens with different recycled aggregate ratios under heat curing.

causes freezing and thawing, especially when exposed to rapidly changing temperatures. Figures 22 and 23 show the total absorption values for cubic specimens with different recycled aggregate for both air and heat curing, respectively. The absorption increased with the incorporation of RCA which has a minimum absorption of 0%. RCA is more porous than natural aggregate which absorbs more water, leading to higher water absorption, by using heat curing the absorption decreased. The results of absorption for (RAPC) specimens under air and heat curing showed a continuous decrease with increasing the replacement ratio. Under air curing the recycled aggregate 10 years reached 5.3% while for the 20 years recycled aggregate it showed 6.1% with 80% replacement. Under heat curing the results showed a lower absorption rate with increasing the replacement ratio reaching 4.4% and 4.9% with 80% replacement for 10 and 20 years recycled aggregate respectively.

Figure 24: A- cracks in heat cured specimen, B- cracks in air cured specimen.

This variation in absorption values is attributed to the fact that the resin filled the pores and cracks due to the accelerated polymerization process and the polymer was employed to cover the surface, also due to good compacting and high dispersion of polymer particles in the aggregate under heating, while the behaviour of higher absorption occurred due to the porous old mortar adhering to the surface of the recycled aggregate, which caused to absorb moisture faster when mixing the components compared to natural aggregates.

4.6. Failure mode

Concrete materials exhibit various failure modes under different loading conditions, with cracks, particularly those associated with the interfacial transition zone (ITZ), playing a pivotal role in compressive and tensile load failure. Understanding these failure mechanisms is essential for enhancing concrete elements' durability and structural integrity in construction projects. The replacement of natural aggregates with recycled aggregates in polymer concrete specimens has been shown to reduce mechanical properties, suggesting alterations in failure behaviour over time. Furthermore, differential failure behaviour are observed in polymer concrete specimens cured under air and heat curing conditions, with notable variations in compressive and splitting tensile strengths values. This highlights the critical role of curing methods in determining material performance. In order to obtain a more comprehensive understanding of the causes of failure and the properties of the materials, a microstructural investigation was performed using SEM imaging. The analysis specifically focused on the features of the resistance of pores and the aggregates in recycled aggregate polymer concrete.

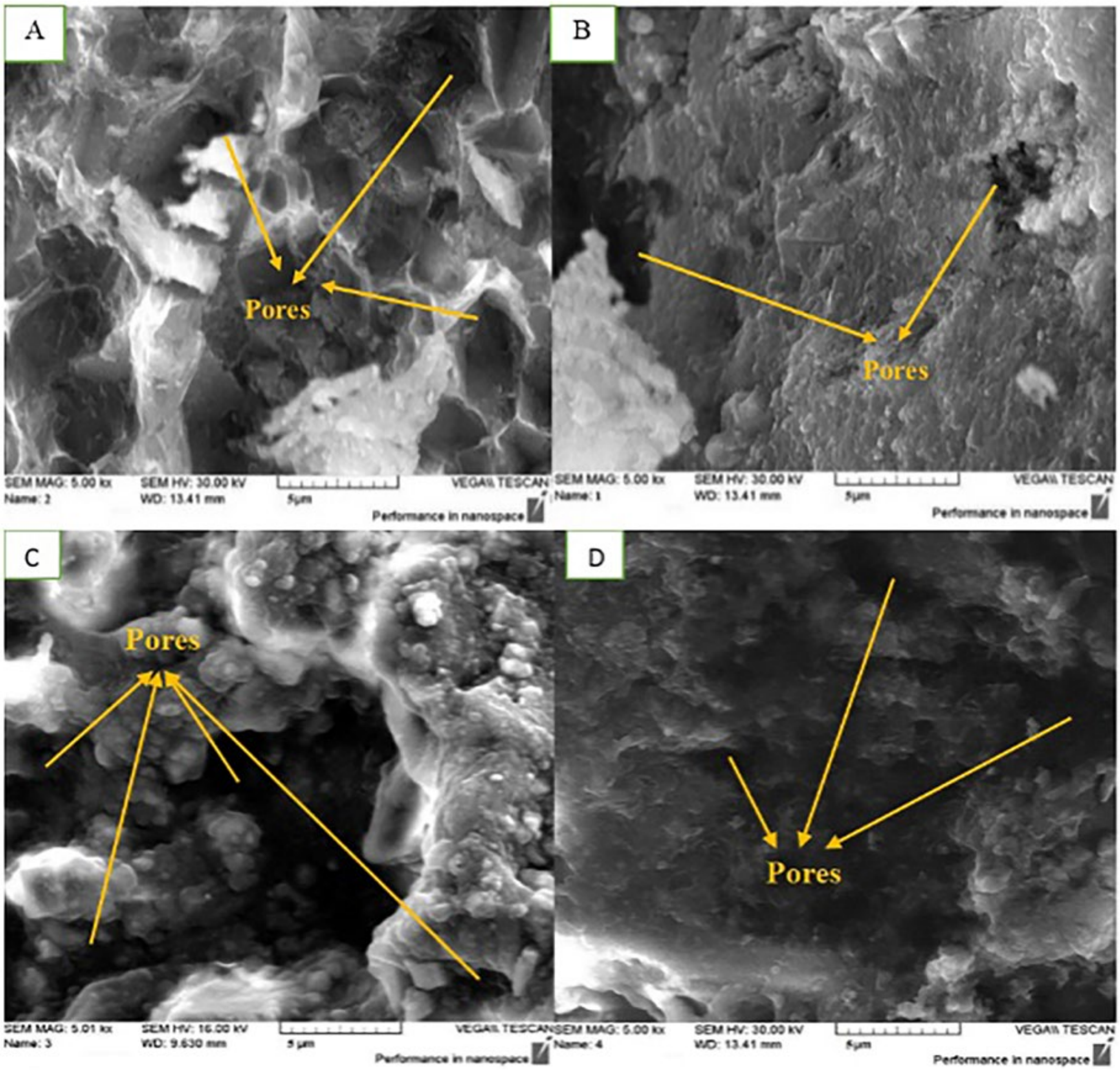

Figure 25: (A) 20% 10 years under air curing, (B) 20% 10 years under heat curing, (C) 20% 20 years under air curing, (D) 20% 20 years under heat curing.

Figure 24 illustrates the cracks after compressive and splitting tensile strength tests for Recycled Aggregate Polymer Concrete (RAPC) specimens under both air curing and heat curing. The cracks in heat cured specimens occurred within the coarse aggregate itself (aggregate splitting) due to the high bonding between the aggregate and the resin, while in air curing the cracks occurred between the coarse aggregate and the bonding mortar. The figure also depicts visual representations of cracks in the specimens, highlighting potential areas of weakness or failure in the concrete elements under different curing environments.

4.7. Scanning electron microscope

The use of microscopic analysis, particularly scanning electron microscopy (SEM), has substantially enhanced the study of concrete microstructure. The use of SEM improves the ability to describe the concrete microstructure and will help in analyzing the effect of concrete mixture, evaluating concrete durability issues, and predicting service life [56].

Proper specimen preparation procedures facilitate the investigation and interpretation of microstructural characteristics in any microscopical technique. Improper preparation procedures might lead to misinterpretation. SEM imaging demands a highly polished surface.

SEM examination was performed on sample pieces obtained following the compressive strength test. This test investigates the microstructure of the prepared RAPC. Interstitial transition zone (ITZ) around aggregate is an important part of the polymer matrix and its composition that would provide insight into the mechanical properties of concrete. RAPC with 20% of 10 and 20 years for both air and heat curing were selected for analysis as shown in Figure 25. As a result, the SEM analysis method is proposed to classify the aggregate's shape and pores within the prepared RAPC. The SEM analysis findings indicates that, various pore and interfacial transition zone (ITZ) appear under air curing which results in lower strength, also indicates that the 20 years recycled aggregate is more irregular in shape.

5. CONCLUSIONS

This study demonstrates that heat curing significantly enhances the mechanical performance of Recycled Aggregate Polymer Concrete (RAPC), enabling high replacement ratios while maintaining strength and durability. The following are the concluding remarks:

- Improved mechanical performance: the study has shown that thermal curing significantly enhances the performance of recycled aggregate polymer concrete (RAPC), helping to compensate for the loss of strength associated with high replacement ratios.
- Optimum replacement ratio: RAPC containing up to 60% recycled aggregate can maintain high compressive strength of up to 65 MPa when applied to the thermal curing, while 80% replacement results in a greater reduction in strength.
- Effect of Aggregate Age: The results showed that recycled aggregate from 10-year-old buildings provided better mechanical performance than aggregate from 20-year-old buildings, indicating a clear effect of source age on RAPC properties.
- Added Scientific Value: Research proves that thermal hardening is an effective technique for improving the properties of RAPC, making it a practical option for sustainable construction and reducing dependence on natural resources.
- Future research recommendations: To optimize RAPC for practical use, further studies should explore long-term durability, different resin formulations, and focus on quantifying air content in RAPC under varying curing temperatures and aggregate ages.

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