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Investigation of the Engineering Properties of Mortars Produced Using Recycled Asphalt Pavements and Pumice Powder under the Effect of Acid

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Research Article

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Abstract

Asphalt pavements play a fundamental role in the formation of the road superstructure and after completing their service life, they are excavated for renewal works and waste materials are produced. The use of such wastes provides economic and environmental advantages, enabling energy saving, reduction of environmental pollution, cost reduction and reduction of landfill areas. Recycled asphalt waste (RAP) has an important place in sustainable material use. In this study, the engineering properties of mortars with Pumice Powder (PP) in hydrochloric acid (HCl) environment were evaluated in detail. In the study, CEM I 42.5/R type Portland cement was used as binder, PP as mineral additive, and 0-4 mm crushed sand and RAP were used as fine aggregate. In the experimental design, different mixtures were obtained by replacing 10%, 20% and 30% of the cement weight with PP, and 0%, 25%, 50%, 75% and 100% of the crushed sand with RAP. Spreading, water absorption, porosity, ultrasonic transmission rate, capillary water absorption, flexural and compressive strength tests were applied to the produced mortar samples after 7 and 28 days of standard curing period of the samples. In addition, the physical and mechanical changes were investigated by exposing the samples kept in the curing pool for 28 days to the HCl solution for 7 and 28 days. The results revealed that the best performance was obtained when PP was used at a rate of 10% and RAP was used at a rate of 25%.

Keywords: Recycled asphalt waste, pumice powder, hydrochloric acid, acid resistance

Geri Dönüştürülmüş Asfalt Kaplama ve Pomza Tozu Kullanılarak Üretilen Harçlarin Asit Etkisi Altında Mühendislik Özelliklerinin İncelenmesi

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Öz

Asfalt kaplamalar, yol üst yapısının oluşturulmasında temel bir işlev görür ve servis ömürlerini tamamladıktan sonra yenilenme çalışmaları için kazılarak atık malzemeler üretilirler. Bu tür atıkların kullanılması, ekonomik ve çevresel avantajlar sağlayarak enerji tasarrufunu, çevresel kirliliğin azaltılmasını, maliyetin düşürülmesini ve depolama alanlarının azaltılmasını mümkün kılar. Geri dönüştürülmüş asfalt atıkları (RAP), sürdürülebilir malzeme kullanımında önemli bir yere sahiptir. Bu çalışmada, Pomza Tozu (PP) katkılı harçların hidroklorik asit (HCl) ortamında sergilediği mühendislik özellikleri detaylı bir şekilde değerlendirilmiştir. Çalışmada bağlayıcı olarak CEM I 42.5/R tipi portland çimentosu, mineral katkı maddesi olarak PP ve ince agrega olarak 0-4 mm boyutlarında kırma kum ile RAP kullanılmıştır. Deneysel tasarımda, çimento ağırlığının %10, %20 ve %30'u PP ile, kırma kumun ise %0, %25, %50, %75 ve %100'ü RAP ile değiştirilerek farklı karışımlar elde edilmiştir. Üretilen harç numunelerine yayılma, su emme, porozite, ultrasonik geçiş hızı, kapiler su emme, eğilme ve basınç dayanımı testleri, numunelerin 7 ve 28 günlük standart kür süresinden sonra uygulanmıştır. Ayrıca 28 gün kür havuzunda bekletilen numuneler, HCl çözeltisinde 7 ve 28 gün maruz bırakılarak fiziksel ve mekanik değişiklikler incelenmiştir. Sonuçlar, PP'nin %10 oranında ve RAP'nin %25 oranında kullanıldığı durumlarda en iyi performansın elde edildiğini ortaya koymuştur.

Anahtar Kelimeler: Geri dönüştürülmüş asfalt atığı, pomza tozu, hidroklorik asit, asit direnci

Introduction

Various industrial wastes are generated worldwide every year and the storage of these wastes is an increasingly important problem. At the same time, recycling waste materials is one of the methods to reduce environmental pollution. Especially RAP contains a bituminous material that occurs in superstructure repair processes. Reuse of this waste material with cement-based materials provides environmental and economic benefits [1]. Using different waste materials instead of aggregates and cement, which are among the sustainable construction materials, has recently been the subject of study by many researchers [2-4]. In addition, as a result of the use of waste materials, costs are reduced, energy is saved, natural resources are protected, and storage areas are reduced [5-7]. It is known that millions of tons of asphalt pavement wastes, which are among these wastes, are generated worldwide every year. These wastes are stored in waste areas after completing their service life and are obtained by excavation during road renovation projects. Using asphalt wastes as aggregates; While the aggregates provide stability, bitumen provides binding and durability properties in mixtures [8-10]. In this context, studies on the re-use of aggregates obtained from RAP in concrete or mortar have become widespread recently [11-15]. Mineral admixtures are used together with RAP to increase the mechanical and durability properties of concrete or mortar. These admixtures include blast furnace slag, silica fume, fly ash and PP. Pumice is a porous material formed as a result of volcanic activities and mortar or concrete containing PP is lighter than standard mixtures and saves labor and time [16]. There are various studies where PP is included in the mixture by replacing cement as a mineral admixture [17-19]. In addition, another reason for using mineral admixtures is to improve durability properties. Cement-based materials are exposed to chemical effects such as chloride ingress, carbonation, alkali attack, sulfate and acid attacks [20-22]. In mortars subjected to acid attack, it has been observed that the highest risk of cracking is on the casting surface and calcium chloride salt accumulates in the acid contact areas. The presence of soluble calcium salts may negatively affect acid resistance [23-25]. The rate and mechanism of acid attack vary depending on various factors such as the type of acid solution, the type of cementitious material, pH value, water/binder ratio and temperature [26, 27]. In recent years, the use of polypropylene fibers and RAP has become widespread in order to increase the durability of concrete and mortars.

Polypropylene fibers offer advantages such as reducing crack formation in concrete, increasing impact strength, and improving resistance to acid and alkaline environments. For example, in a study conducted by Kantarcı [28], it was determined that polypropylene fibers added in different lengths and ratios significantly increased the acid resistance of geopolymer concretes against 5% HCl solution and prevented crack formation. These findings show that polypropylene fiber addition improves the performance of concrete in acidic environments. In addition, RAP aggregate stands out as an important material in terms of protecting natural resources and reducing the amount of waste [28]. In another study, Karademir et al. observed increases of up to 1941% in flexural toughness in mortars with waste polypropylene fiber added at 0.2–1.5% volumetric ratios compared to reference samples without fibers [29]. In addition, fiber addition increased the ductile behavior of mortars and reduced the tendency for brittle fracture. In a study conducted by Alakara [30], the use of RAP powder in alkali-activated slag mortars was investigated. The results showed that the use of RAP powder increased the resistance to sulfuric acid and reduced porosity and water absorption values [30]. The main purpose of the study is to reduce energy consumption, environmental pollution and costs by using RAP, and to contribute to recycling by minimizing the need for storage space. In this direction, the engineering properties of mortars produced with RAP and PP under acid effect were evaluated. CEM I 42.5/R type cement was used as binder in the samples, PP as mineral additive and RAP with 0-4 mm crushed sand as aggregate. In the study, PP was replaced by 10%, 20% and 30% of the cement weight, and RAP was replaced by 0%, 25%, 50%, 75% and 100% of the crushed sand. The physical, mechanical properties of the prepared samples and weight losses under acid effect were analyzed.

Materials and Methods

Material

CEMI-42.5/R type cement, which complies with TS EN 197-1 standards, was used as the binder in the mixture of mortar samples produced for the experimental study [31]. The properties of the cement used are presented in Table 1.

Table 1*. Physical and chemical properties of CEM I 42.5/R type cement used in the experiment*

Analiz	Oxide	Value	Analiz	Experiments	Value
Chemical Analysis (%)	CaO	62.63	**Physical Analysis**	Fineness (cm^2/g)	3400
	Al_2O_3	5.65		Intensity, g/cm3	3.12
	SiO_2	20.62		Beginning of set (min)	260
	Fe_2O_3	4.05		Ending of set (min)	300
	SO_3	2.57		Volume expansion, mm	2.00
	MgO	2.58	**Compressive strength (MPa)**	2. day	32.5
	Loss on ignition	1.55		7. day	43.4
	Insoluble Residue	0.35		28. day	53.6

Crushed sand aggregate with a grain size of 0-4 mm in accordance with TS 706 EN12620 + A1 standard was used in sample production [32]. RAP of various sizes was brought to 0-4 mm grain sizes using the jaw crusher in Figure 1a. RAP with a grain size of 0-4 mm used in mortar production is shown in Figure 1b, and the granulometry curve of the RAP used is shown in Figure 1c.

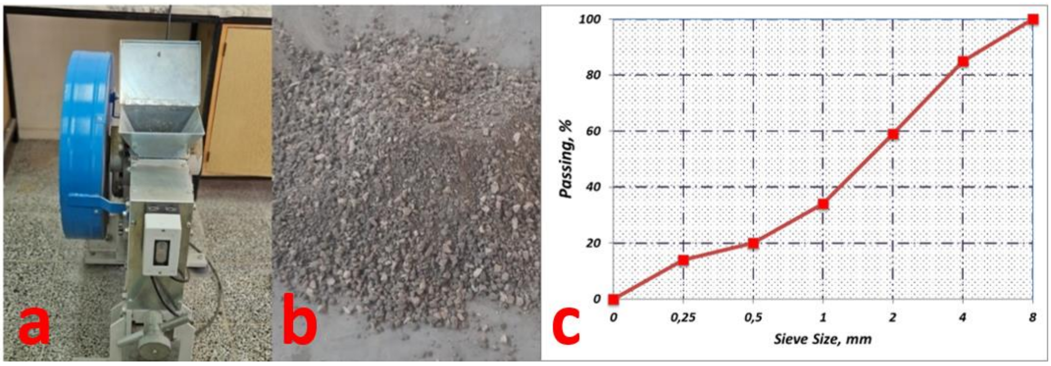

Figure 1. *Jaw crusher (a), RAP (b) and Granulometry curve of RAP (c)*

The PP used as a replacement for cement was ground in the ring mill shown in Figure 2a and the grain size was brought to the range of 25-35 microns (Figure 2b). The physical and chemical properties of the PP replaced with cement are presented in Table 2.

Figure 2. *Ring mill used in the experiment (a) and PP (b)*

Table 2. *Chemical analysis of PP*

Chemical Components	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	SrO	P_2O_5	Cr_2O_3	Value
Content Ratios (%)	51.20	20.70	1.24	0.05	6.00	1.60	11.38	0.05	0.03	0.05	7.7

In the production of mortar samples, potable city tap water supplied in accordance with TS EN 1008 standard was used [33]. In order to examine the HCl acid effect of mortars, HCl acid with a density of 1.15-1.16 g/cm^3 and a purity of 30-32% in accordance with TS-EN ISO 9001 standard was preferred [34].

Method

The material amounts of the samples used in the experimental study are presented in Table 4. Mortars were prepared by replacing 0%, 10%, 20% and 30% of the cement weight with PP and 0%, 25%, 50%, 75% and 100% of the crushed sand weight with RAP. The coding of the samples is shown in Figure 3 in order to indicate the RAP and PP usage rates. A spreading table test was carried out in accordance with TS EN 1015-3 standard to evaluate the workability of fresh mixtures [35]. Then, the mortars taken into steel prism molds with dimensions of 40x40x160 mm were placed using a shaker. The samples, which were kept in the molds for 24 hours, were then stored in the standard curing pool for 7 and 28 days. At the end of this period, water absorption, porosity, ultrasonic transmission rate and capillary water absorption were applied to the samples. Flexural strength tests (three-point) and compressive strengths test of the mortars were performed on 3 samples in accordance with TS EN 196-1 standard and presented as average (Figure 4) [36]. Flexural strength tests was carried out with the help of a strength device with a loading capacity of 20 kN and a compressive strength test with a loading capacity of 200 kN. Samples that completed the 28-day curing period were exposed to the acid solution for 7 and 28 days.

Table 4. *Amounts of materials required for sample production (g)*

Sample Name		Crushed Sand	Cement	Water	RAP	PP
RAP0	PP0	1350	450	225	0	0
	PP10	1350	405	225	0	45
	PP20	1350	360	225	0	90
	PP30	1350	315	225	0	135
RAP25	PP0	1012.5	450	225	337.5	0
	PP10	1012.5	405	225	337.5	45
	PP20	1012.5	360	225	337.5	90
	PP30	1012.5	315	225	337.5	135
RAP50	PP0	675	450	225	675	0
	PP10	675	405	225	675	45
	PP20	675	360	225	675	90
	PP30	675	315	225	675	135
RAP75	PP0	337.5	450	225	1012.5	0
	PP10	337.5	405	225	1012.5	45
	PP20	337.5	360	225	1012.5	90
	PP30	337.5	315	225	1012.5	135
RAP100	PP0	0	450	225	1350	0
	PP10	0	405	225	1350	45
	PP20	0	360	225	1350	90
	PP30	0	315	225	1350	135

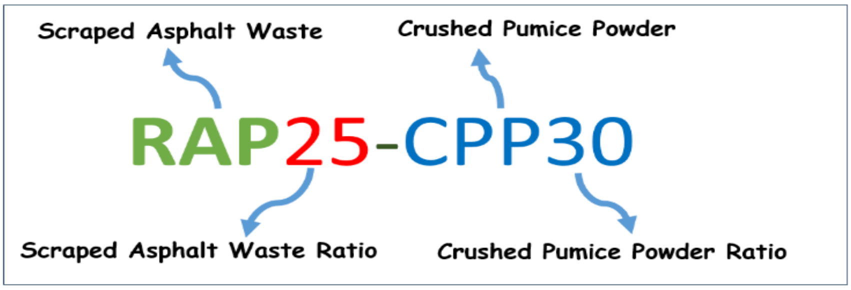

Figure 3. *Coding scheme of sample names*

Figure 4. *Flexural strength tests (three-point) and compressive strengths test*

Findings

Strength Index

The activity in terms of strength in ASTM C618 should be 75% and above the value found by comparing the 28-day compressive strength values (41.75 MPa) of PP at 20% of the cement content with the 28-day compressive strength values (52.85 MPa) of mortar samples produced using only Portland cement [37]. If this value is 75% and above, the material used is considered as pozzolan. The activity index of PP was calculated as 79%.

Slump Test

The results of the spreading table test performed to evaluate the workability properties of fresh mortar samples are presented in Figure 5. It can be said that as the PP substitution rate increases, the reason for not reaching the desired spreading value is due to the large number of pores and high surface area in the PP grain structure [16, 38]. When the spreading results of the produced mortar samples are examined, it is seen that the RAP25, RAP50, RAP75 and RAP100, PP10, PP20, PP30 samples are reduced by 7.46%, 13.43%, 17.91%, 20.90%, 5.97%, 7.46%, 8.96%, respectively, when compared to the RAP0-PP0 sample. It is thought that the loss of workability due to the fine-grained nature of PP is due to the need for more water absorption [39].

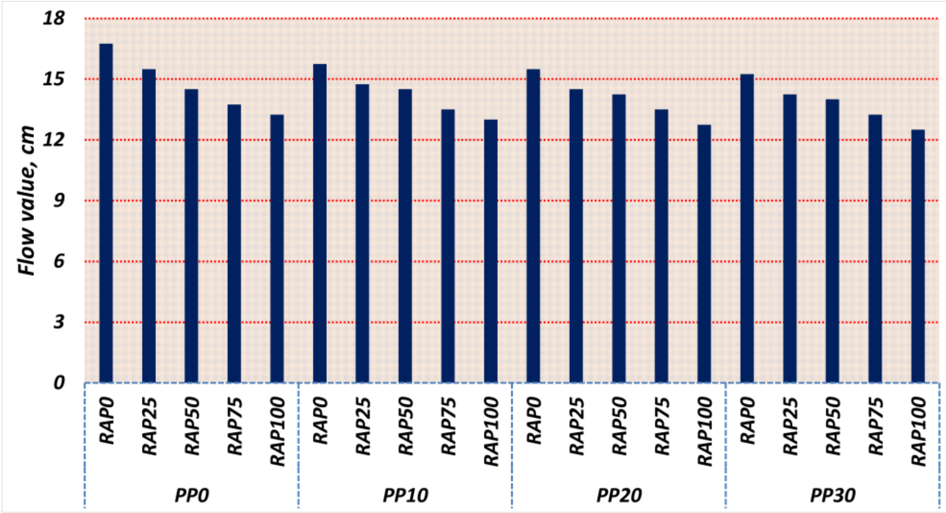

Figure 5. *Flow values of fresh mortar samples*

Water Absorption Before and After Acid

The 28-day water absorption rates of PP-added mortar samples produced using RAP before and after acid treatment are shown in Figure 6. According to the results obtained at the end of 28 days, the highest water absorption rate was determined as 9.43% in the RAP100-PP30 sample, while the lowest water absorption rate was determined as 7.76% in the R sample. The water absorption rates of RAP25, RAP50, RAP75, RAP100, PP10, PP20 and PP30 samples increased by 2.96%, 4.38%, 4.77%, 6.31%, 3.99%, 5.03% and 7.22%, respectively, compared to the R sample. An increasing trend in the water absorption rate was observed with the increase in the RAP and PP substitution rates. However, it was stated that the water absorption rate decreased as the PP rate increased, and this was due to the fact that PP filled the pores and reduced water movement in the voids within the sample [40]. When the water absorption rates of the samples kept in HCl acid solution for 28+28 days were examined, the highest water absorption rate was observed in the RAP100-PP30 sample and the lowest in the RAP25 sample. It was stated that HCl caused disintegration in cement-based materials and damaged the cement structure by forming calcium chloride [41]. The pore filling effect of PP improved the performance by reducing the water absorption rate in the acid environment [40]. In addition, the accumulation of hydrated cement paste on the RAP surface and the fact that the recycled fine aggregate had a higher water absorption rate than natural sand support the results [42].

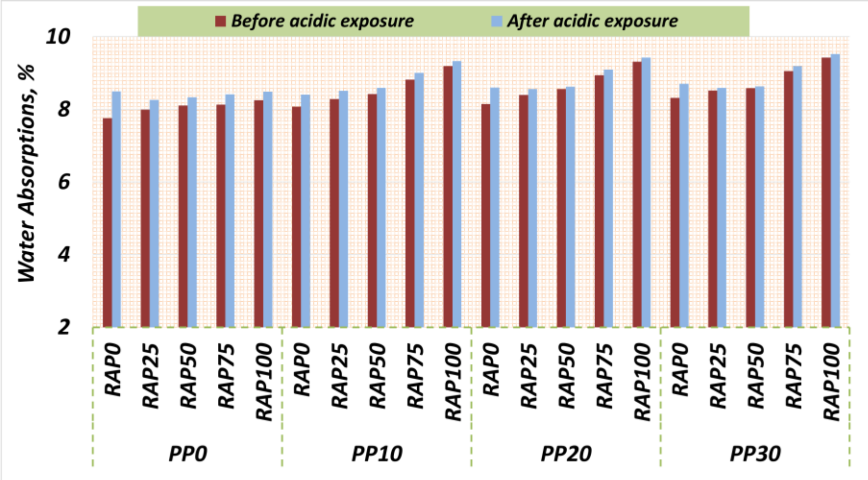

Figure 6. *Water absorption values of mortar samples*

Porosity Before and After Acid

The porosity values of the samples before and after acid treatment are shown in Figure 7. When the porosity rates obtained after 28 days were examined, the highest porosity rate was determined in the RAP100-PP30 sample and the lowest porosity rate was determined in the RAP0-PP0 sample. As the RAP and PP substitution rates increased, the porosity rates increased.

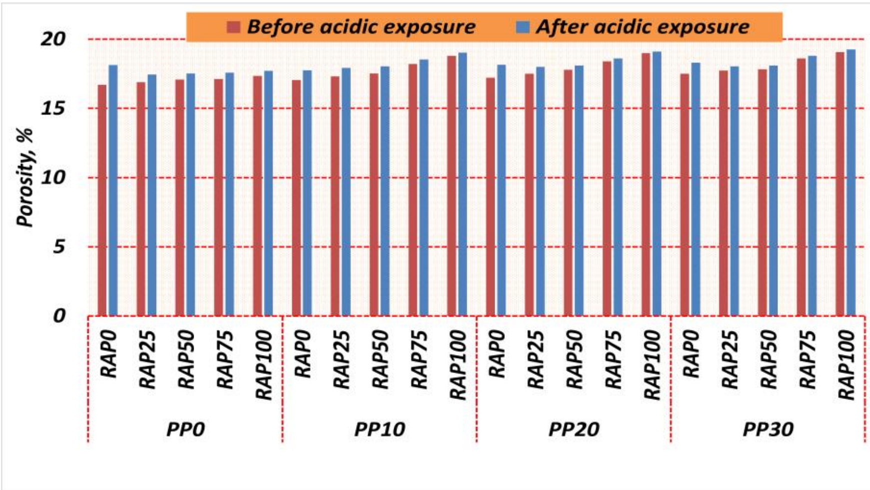

Figure 7. *Porosity ratios of mortar samples*

When the porosity rates of the mortar samples exposed to the HCl acid solution with a concentration of 5% for 28 days were examined, the highest porosity rate was found in the RAP100-PP30 sample, and the lowest porosity rate was found in the RAP25 sample. As the RAP and PP substitution rates increased, the porosity rates of the 28-day samples waiting in HCl acid increased [43]. When PP is added, its total porosity increases and can lead to deterioration of its properties. PP has a high porosity [44, 45].

Ultrasonic Pulse Velocity

When the 28-day results of the samples are examined in Figure 8, it is seen that the highest value is taken from the R sample and the lowest value is taken from the RAP100-PP30 sample. The voids in the sample and the structure of these voids affect the mechanical properties. It has been observed that as the compressive strength of cement-based composites increases, the ultrasound pulse velocity increases due to the denser internal structure of the concrete or mortar [46, 47]. When the 28-day results of the samples are examined, it is seen that the lowest value of 3306 m/s is taken from the RAP100-PP30 sample.

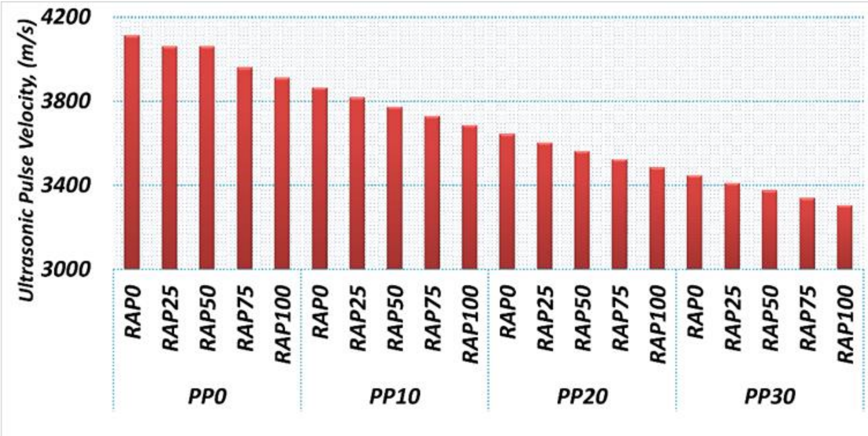

Figure 8. *Ultrasound pulse velocity experience results*

Flexural Strength

According to the 7 and 28-day flexural strength results presented in Figure 9, the highest strength was obtained in the R sample, while the lowest strength was obtained in the RAP100-PP30 sample. In Figure 9, the 28-day final strengths before acid exposure are expressed, while the 7 and 28 days after acid exposure represent the periods of acid exposure after the final strength. With the increase in PP usage rates, a decrease in the flexural strength of all samples was observed [48]. Similar to the flexural strength, a decrease in the compressive strength results was also stated [49]. When the flexural strength results of the samples kept in the HCl acid solution with a concentration of 5% for 7 and 28 days are examined in Figure 10, it is seen that the highest strength is in the R sample, while the lowest strength is in the RAP100-PP30 sample.

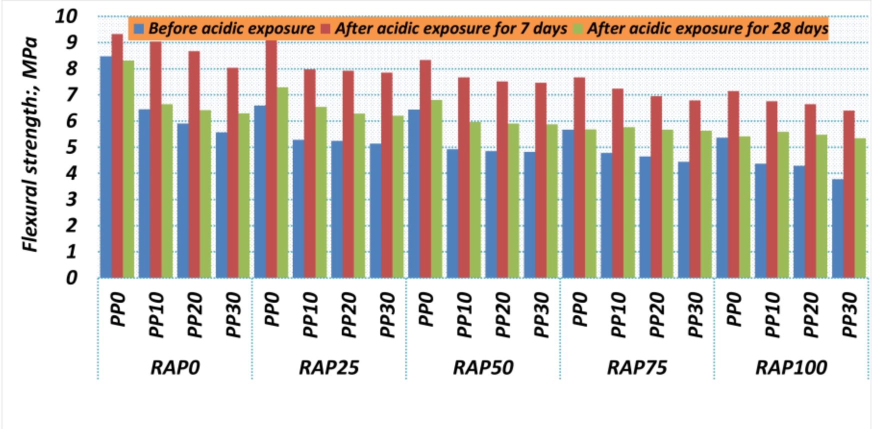

Figure 9. *Flexural strength test results of mortar samples*

Compressive Strength

According to the 7 and 28-day compressive strength results in Figure 10, the highest strength was obtained in the R sample, while the lowest strength was obtained in the RAP100-PP10 sample. In Figure 10, the 28-day final strengths before acid exposure are expressed, while the 7 and 28 days after acid exposure represent the periods of acid exposure after the final strength. It was determined that the use of RAP and PP had a decreasing effect on the compressive strengths of the samples. The 7 and 28-day compressive strengths of the samples containing RAP and PP were found to be lower than those of the RAP0 and PP0 samples [19]. This is because the pozzolanic compounds in PP require more time to react with $Ca(OH)_2$ and the increase in the amount of PP negatively affects the compressive strength [50]. In addition, when the compressive strength data of the samples exposed to HCl acid solution for 7 and 28 days were examined, the lowest strength was determined in the RAP100-PP30 sample, while the highest strength was determined in the R sample. It was observed that the 28-day compressive strength results decreased compared to those before exposure to the acid solution. This decrease was attributed to the HCl solution leaking into the samples, changing the physical and chemical structure of the mortar, and these changes negatively affecting the strength.

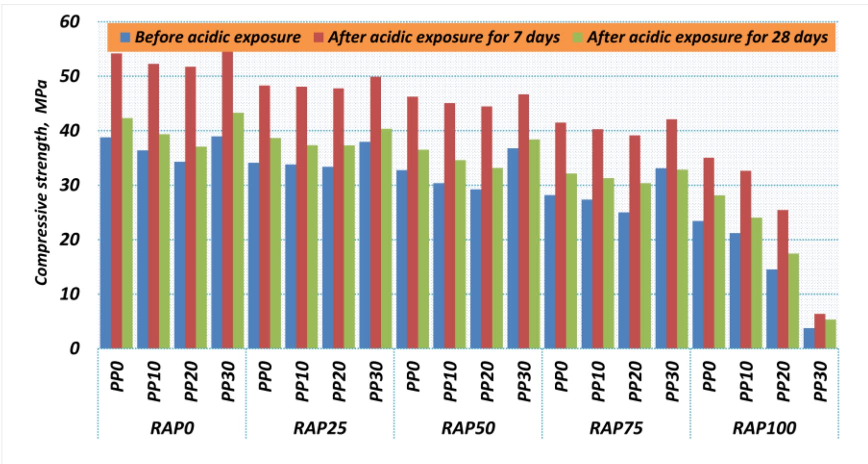

Figure 10. *Compressive strength test results of mortar samples*

Weight Losses After Acid

The weight losses of the samples after exposure to HCl acid with a concentration of 5% by volume for 28 days are given in Figure 11. It was observed that the weight losses in all samples in the graph were between 10% and 14% and that the acid environment created a significant change in the concrete samples. The highest weight loss was found in the RAP100-PP0 sample, while the lowest weight loss was found in the RAP10-PP0 sample. As the RAP ratio increased, an increase in weight loss was generally observed. Higher weight losses were observed especially in the RAP100 sample group. It was observed that the weight loss was less in the groups with lower RAP ratios (RAP25 or RAP50). As the PP addition ratio increased, the weight losses in the samples decreased. The increase in the RAP addition ratio caused weight loss. Generally, lower weight losses were observed in the samples with PP20 or PP30 additives and low RAP content (RAP25 or RAP50). These combinations can be considered as a suitable option in terms of both economic and performance for a concrete design resistant to acidic environments.

Figure 11. *Weight losses of samples exposed to HCl acid after acidification*

The samples kept in the curing pool for 28 days were immersed in a 5% HCl solution for 28 days to analyze the changes in their physical and mechanical properties. The 5% concentration of hydrochloric acid was selected based on its widespread use in durability studies to simulate aggressive acidic environments. For instance, Abubakar et al. [51] utilized a 5% HCl solution to assess the early-age compressive strength of concrete, observing significant strength variations over a 28-day period. Similarly, studies have demonstrated that a 5% HCl solution, with a pH of approximately 0.7, effectively induces measurable degradation in cement-based materials, making it a suitable concentration for evaluating acid resistance in concrete specimens [52, 53]. The visual differences caused by corrosion as a result of acid attacks to which the samples were exposed to HCl with a concentration of 5% by volume are given in Figure 12.

Figure 12. *Visual differences before and after acid in HCl solution*

Conclusions

In this study, the engineering properties of samples produced using both PP and RAP under the effect of acid were investigated and the following results were obtained.

- As PP and RAP ratios increased, decreases were observed in spreading values. This situation shows that workability of mortar decreases with increasing PP and RAP usage rates.
- As sample age increases, changes in water absorption and porosity rates progressed in a similar direction. As RAP and PP substitution rates increase, an increase in water absorption and porosity rates was observed. For example, the water absorption rates of RAP25, RAP50, RAP75, RAP100, PP10, PP20 and PP30 samples increased by 2.96%, 4.38%, 4.77%, 6.31%, 3.99%, 5.03% and 7.22%, respectively, compared to the R sample. This situation shows that the increase in material substitution rates has an effect on water absorption and porosity.
- As RAP and PP ratios increase, an increase in capillary water absorption values was observed. As sample age increases, a decrease in capillary water absorption values was observed. Samples with high porosity rates gave higher results in terms of capillary water absorption values.
- As sample age increases, decreases are observed in flexural and compressive strengths as well as weight losses of samples kept in HCI acid solution.

- It has been determined that the use of RAP and waste materials allows for the reduction of environmental impacts in mortar or concrete production processes, the more efficient and sustainable use of natural aggregates, and thus more economical samples can be produced. Experimental results show that RAP and PP can be an effective alternative in the production of mortar or concrete mixtures.
- Based on the findings of this study, it is recommended to examine the engineering properties of samples using different proportions of mineral and chemical additives in more detail. In particular, comprehensive and detailed research is necessary to better understand the potential use of PP material as a mineral additive.
- It has been observed that the use of RAP and PP has a reducing effect on flexural and compressive strengths. It has been determined that the samples exhibited an acceptable performance in terms of compressive strength value.
- Ultrasound pulse velocity decreased as RAP and PP ratios increased. When the 28-day results of the samples are examined, it is seen that the lowest value of 3306 m/s is taken from the RAP100-PP30 sample. Ultrasound pulse velocity increased as the samples aged. This shows that ultrasound waves propagate faster in mortar samples as the samples gain strength and porosity rates decrease. It is observed that the ultrasound pulse velocity values increase as the sample ages. This situation shows that the ultrasound pulse velocity increases with the samples gaining more strength and decreasing porosity rates over time.
- It was observed that the weight losses in all samples under the influence of acid were between 10% and 14%, and the acid environment caused a significant change in the concrete samples.
- It shows that the increase in RAP and PP usage rates in the samples exposed to HCl solution for 28 days has a decreasing effect on the flexural strength. This situation reveals that the mechanical strength of the samples may decrease under acidic conditions and this effect is more pronounced in the RAP100-PP30 sample.

As a result of this study, it is recommended that future research should evaluate the behavior of mortars containing PP and RAP under different chemical solutions such as sulfate or nitrate environments. In addition to HCl, the effects of other aggressive chemicals such as sulfuric acid or acetic acid can also be included in future investigations. Furthermore, the incorporation of other mineral admixtures such as fly ash, ground granulated blast furnace slag, or silica fume alongside PP and RAP is worth exploring to enhance the durability properties of sustainable mortars.

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Authors Contribution Authors contributed equally to the work

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