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Research paper

Removal of old adhered mortar from crushed concrete waste aggregate (CCWA) with different HCl molarities and its effect on CCWA properties

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Abstract

Removing old adhered mortar from crushed concrete waste aggregates (CCWAs) is essential to ensure the quality of the CCWA used in the production of new concrete. Pre-soaking the CCWA in hydrochloric acid (HCl) solution was reported as an effective technique for the removal of old adhered mortar. However, the data on the treatment of CCWAs with HCl failed to address the influence of HCl molarity on CCWA properties, such as the aggregate crush value, aggregate impact value, and water absorption, and the correlation between treatment variables, such as size of aggregate, time of submersion in HCl, CCWA microstructure, and HCl molarity. Fifteen specimens of CCWA were prepared. One specimen was of untreated CCWA and fourteen specimens were treated; each of these specimens were treated with different HCl molarities of 0.2, 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0 10.0, 11.0, and 12.8. Experimental data were analyzed with SPSS. A 500x digital microscope was used to examine the microstructure surface of the aggregate. Results showed a significant correlation between the HCl molarity and CCWA properties. A higher HCl molarity resulted in better quality of CCWA. Furthermore, the microscope test showed a similar microstructure surface of CCWA when treated with 12.8 HCl.

Keywords: *Recycled Aggregate; Surface Treatment; Crushed Concrete Waste Aggregate; Removing the Old Adhere Mortar; Pre-Soaking Treated Recycled Concrete Aggregate.*

1. Introduction

The potential benefits of using crushed concrete waste aggregates (CCWAs) in concrete have been widely studied. However, the use of CCWA as substitute material for natural aggregates (NAs) has never been preferable in the construction industry [1]–[4]. CCWAs contain approximately 65% NA and 35% adhered mortar. The amount of adhered mortar indicates the characteristics of the original concrete, effectiveness of crushing procedure, and the particle size of CCWAs [5]. A mutual correlation occurs between the adhered mortar and the quality of CCWA. Adhered mortar is greatly responsible for the poorer CCWA properties compared with NAs [1], [3], [6]. The water absorption capacity of CCWAs, is approximately three times more than that of NAs. This capacity of CCWAs depends on the amount of old adhered mortar attached to the surface of aggregate particles [7]–[10]. CCWAs are poorly graded because of their poor particle size distribution [47]. They are either extremely coarse or extremely fine due to inappropriate crushing process. Although CCWA grading can be controlled with a highly precise crushing process, the microcracks developed in the adhered mortar and fractures developed inside the aggregate as result of the crushing process cannot be controlled [11], [12]. Studies have reported that CCWAs generally have lower mechanical properties (such as lower crushing strength and lower impact resistance) than NAs due to the presence of old mortar on the surface of the aggregates [13]–[15].

Thus, the main factor that affects the quality of the CCWAs is that old cement remains on the surface of the aggregates, thereby resulting in high porosity, water absorption, weak interfacial zone between the new cement mortar and the aggregates, and low mechanical properties [16]. Thus, removing old adhered mortar by submerging the CCWAs in hydrochloric acid (HCl) with various molarities (0.2–12.8 ml) to remove the old cement paste adhered on the surface of the CCWA, thereby promoting sustainability. The present work reports the effectiveness of using HCl with various molarities to remove the paste adhered on the surface of CCWA as treatment method and its effect on CCWA properties, such as aggregate crush value (ACV), aggregate impact value (AIV), water absorption, and the relationship between HCl molarity and size of CCWA.

2. Methods

2.1. Materials

The CCWA used in this study was obtained from an old demolished building in Kuala Lumpur, Malaysia. HCl with molar mass of 36.46094 g/mol was used to remove the cement adhered on the surface of the CCWA. Fourteen CCWA specimens was prepared and treated with different HCl molarities, and one CCWA was untreated. All CCWA aggregate specimens were experimented on and compared with NAs. Each of these CCWA specimens was subjected to the same experimental procedure. Table 1 shows the CCWA specimens linked to different HCl molarities. Two jaw crushers at the UiTM laboratory were used to crush CCWAs to ensure good size distribution. Furthermore, CCWA was crushed to sizes of 10 mm and 20 mm. CCWAs were sieved, and all the undesired particles were either eliminated or recrushed.

Fig. 1: Specimens of CCWA.

Table 1: Specimens of CCWA Linked to Different Molarity of HCL

CCWA specimens	Description
NA	Natural Aggregate
CCWA0.0H	Untreated CCWA aggregate
CCWA0.2H	CCWA aggregate treated with HCL of molarity 0.2 (ml)
CCWA0.5H	CCWA aggregate treated with HCL of molarity 0.5 (ml)
CCWA1.0H	CCWA aggregate treated with HCL of molarity 1 (ml)
CCWA2.0H	CCWA aggregate treated with HCL of molarity 2 (ml)
CCWA3.0H	CCWA aggregate treated with HCL of molarity 3 (ml)
CCWA4.0H	CCWA aggregate treated with HCL of molarity 4 (ml)
CCWA5.0H	CCWA aggregate treated with HCL of molarity 5 (ml)
CCWA6.0H	CCWA aggregate treated with HCL of molarity 6 (ml)
CCWA7.0H	CCWA aggregate treated with HCL of molarity 7 (ml)
CCWA8.0H	CCWA aggregate treated with HCL of molarity 8 (ml)
CCWA9.0H	CCWA aggregate treated with HCL of molarity 9 (ml)
CCWA10.0H	CCWA aggregate treated with HCL of molarity 10 (ml)
CCWA11.0H	CCWA aggregate treated with HCL of molarity 11 (ml)
CCWA12.8H	CCWA aggregate treated with HCL of molarity 12.8 (ml)

Fig. 2: Jaw Crushers at the UITM Laboratory Treatment of CCWA.

Fourteen CCWA specimens were prepared and oven-dried for 24 h. The weights of the oven-dried CCWA specimens were recorded. Each CCWA specimen was submerged for 72 h in HCl with different molarities, as presented in Table 1. The weights of CCWA specimens were then recorded at 4, 8, 24, 48, and 72 h after being oven-dried. Subsequently, the CCWA specimens were returned to the HCl solution after each weight measurement until the end of the treatment period. The weight loss of the CCWA specimens were recorded at 4, 8, 24, 48, and 72 h.

Fig. 3: Specimens of CCWA Soaked the HCL with Different Molarity.

3. Results and discussion

3.1. CCWA treatment

The CCWA specimens were crushed to sizes larger than 25 mm and were submerged in HCl for 3 d. The weight loss of the CCWAs was calculated after 4, 8, 24, 48, and 72 h. The weight loss occurred due to the dissolving of the old mortar adhered on the surface of the aggregates.. Fig 4 shows that the weight loss of the CCWA specimens increased with the HCl molarity. The HCl with molarities of 0.1 and 0.5 were sufficient for producing a good CCWA. However, the experimental results showed that HCl with molarities of 0.2 and 0.5 lost only 1.7% and 1.8% of the total weight of the CCWA. By contrast, other specimens that were treated with higher HCl molarity recorded more weight loss of up to 20% of the total weight of the CCWA. (Ismail & Ramli, 2013b). The HCl with low molarity removed the loosely adhered mortar attached to the original aggregate, which explained the low percentage of weight loss when HCl with molarities of 0.2 and 0.5 was used. (V. W. Y. Tam, Tam, & Wang, 2007).

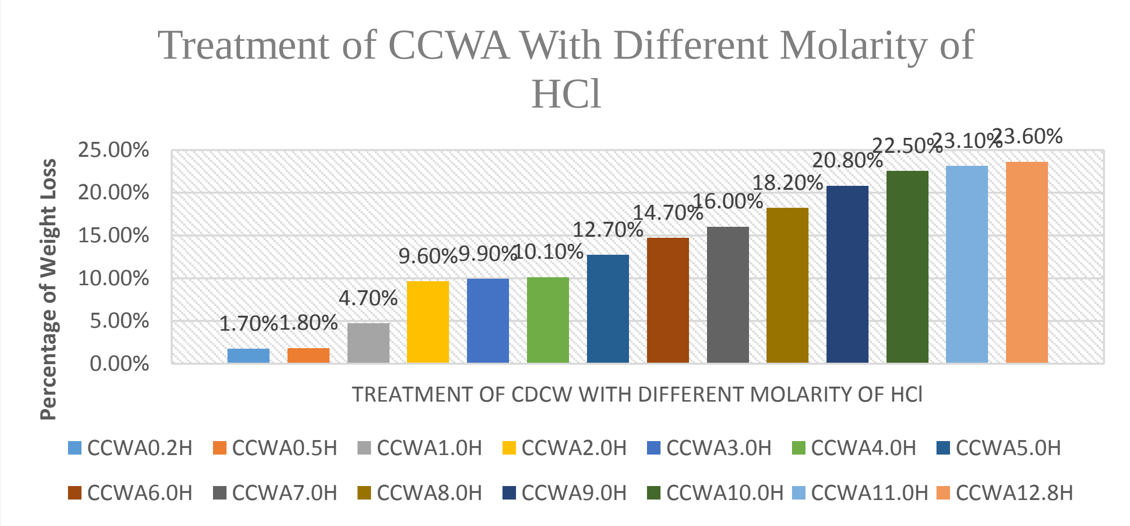


Fig. 4: Treatment of CCWA with Different Molarity of HCl.

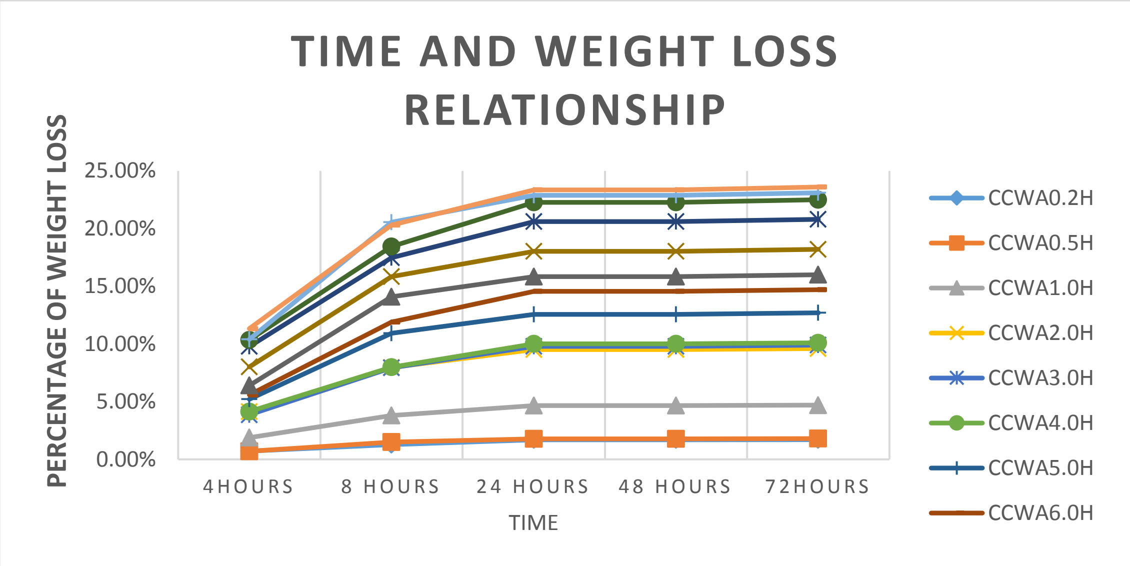
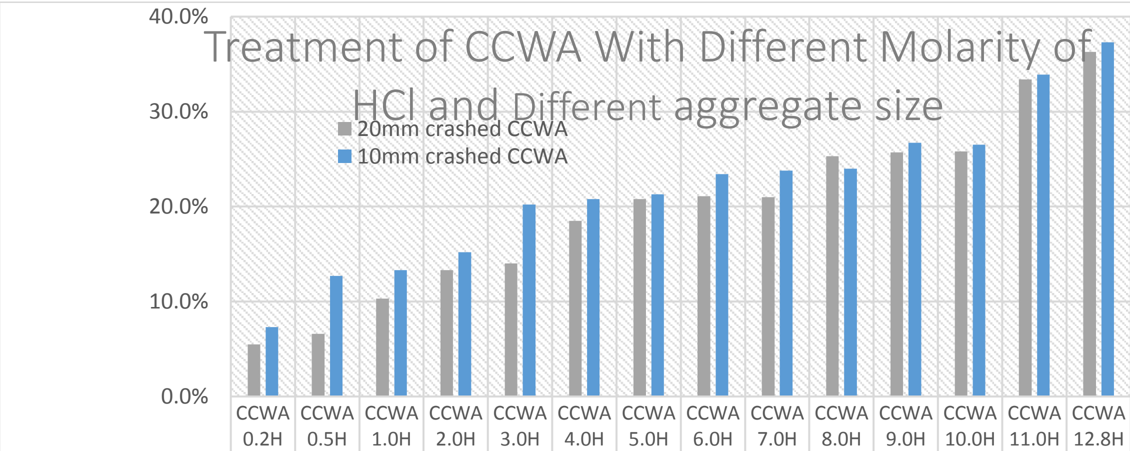


Fig. 5: Time and Weight Loss Relationship.



	CCWA 0.2H	CCWA 0.5H	CCWA 1.0H	CCWA 2.0H	CCWA 3.0H	CCWA 4.0H	CCWA 5.0H	CCWA 6.0H	CCWA 7.0H	CCWA 8.0H	CCWA 9.0H	CCWA 10.0H	CCWA 11.0H	CCWA 12.8H
20mm crashed CCWA	5.5%	6.6%	10.3%	13.3%	14.0%	18.5%	20.8%	21.1%	21.0%	25.3%	25.7%	25.8%	33.4%	36.3%
10mm crashed CCWA	7.3%	12.7%	13.3%	15.2%	20.2%	20.8%	21.3%	23.4%	23.8%	24.0%	26.7%	26.5%	33.9%	37.3%

Fig. 6: Treatment of CCWA with Different Molarity of HCL and Different Aggregate Size.

Fig 5 shows the development of the treatment of CCWAs within 3 d. Despite the difference in HCl molarities, all CCWA specimens stopped reacting with the HCl after 24 h. Prior studies (Güneyisi, Gesoğlu, Algın, & Yazıcı, 2014; Ismail & Ramli, 2013a, 2014; V. W. Y. T. C. M. Tam & Le, 2007) have focused on HCl as a treatment agent to remove the old mortar adhered on the surface of the aggregate. Some of these studies have suggested that the RCA was to be immersed for 3 d, whereas others reported that 24 h was sufficient for RCA treatment. However, no research has focused on the time needed for the CCWA to react fully with HCl.

Fig 6 shows the effects of different HCl molarities on the size of the CCWAs. The Figure shows a relationship between the size of the CCWAs and weight loss. The results from Fig s 4 and 6 show that the HCl has a high corrosion effect on small-sized aggregates, which results in approximately 50% further weight loss (old adhered mortar loss). Despite the different HCl molarities, the CCWAs showed significant weight loss. For example, the percentage of weight loss increased from 1.7% and 1.8% to 5.6% and 6.7% when 20 mm CCWA was submerged in HCl with molarities of 0.2 ml and 0.5 ml, respectively. The increase in weight loss of the small-sized CCWA when submerged in HCl was due to the increase of the surface area that reacted with the HCl. Submerging CCWA in an acidic solution, such as HCl, has been conducted by many researchers; nevertheless, prior studies have reported the effect of size on the pre-soaking treatment method (Güneyisi et al., 2014; Ismail & Ramli, 2014; Purushothaman, Amirthavalli, & Karan, 2000a; Saravanakumar, Abhiram, & Manoj, 2016; Shi et al., 2016; V. W. Y. T. C. M. Tam & Le, 2007; Zaharieva, Buyle-Bodin, Skoczylas, & Wirquin, 2003).

3.2. Properties of treated CCWA

Fig 7 and Fig 8 show the experimental results of the ACV and AIV conducted on 14 CCWAs treated with different HCl molarities and one untreated CCWA. ACV and AIV indicated the strength of the aggregates. These values are expressed as a percentage of the total weight. A lower percentage indicates tougher and stronger aggregates. From the results of the ACV experiment, the untreated CCWA exhibited the highest value with 38.6%. Treating CCWAs improved the ACV value; likewise, the CCWAs treated with low HCl molarity exhibited up to 50% higher ACV values than CCWAs treated with high HCl molarity. Similarly, Fig 8 shows that the untreated CCWA recorded the highest value of AIV with 39.1%. Treating CCWAs improved the ACV value; likewise, the CCWAs treated with low HCl molarity was up to 55% higher than CCWAs treated with high HCl molarity. ACV and AIV improved with the increase in HCl molarity. Recycled aggregates have been reported to exhibit high ACV and AIV with almost 36% and 31%, respectively; they also have better ACV and AIV at 33% and 29%, respectively, when treated with HCl molarity of 0.1 ml (Kumar, Dhinakaran, & Ph, 2012; Purushothaman, Amirthavalli, & Karan, 2000b; Purushothaman et al., 2000a).

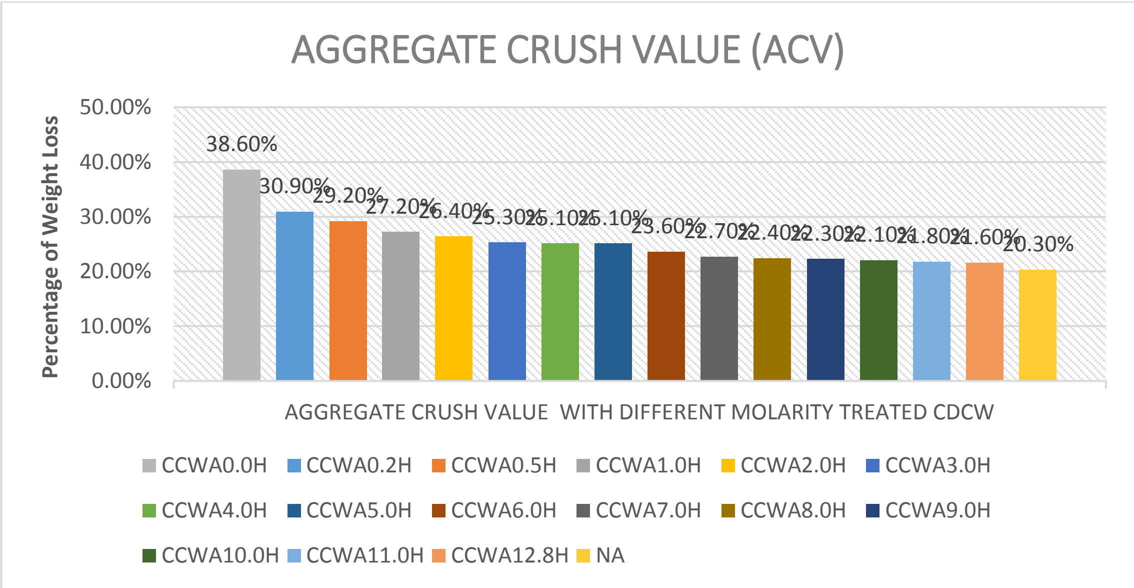


Fig. 7: Aggregate Crush Value with Different Type of Treated CCWA with Different Molarity.

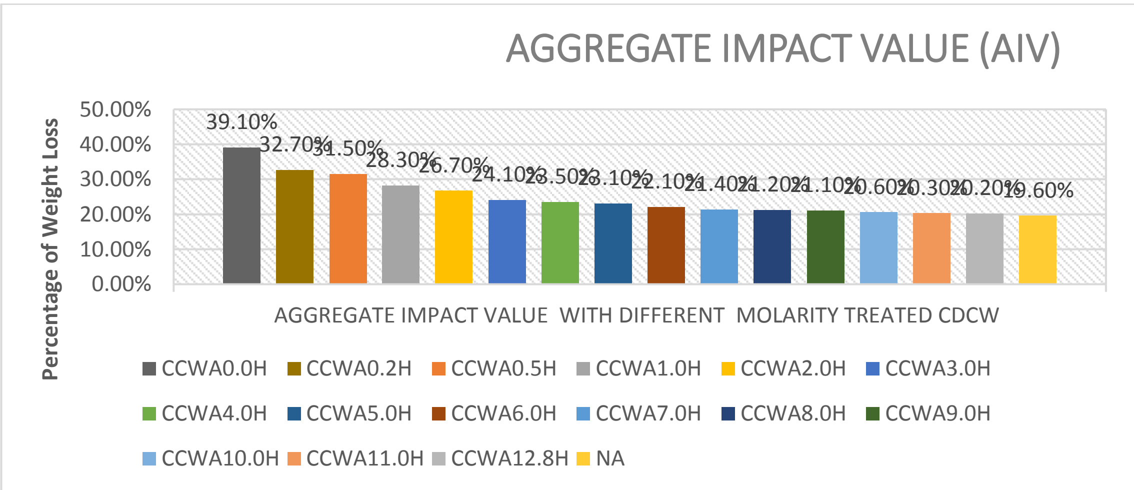


Fig. 8: Aggregate Impact Value with Different Molarity Treated CCWA.

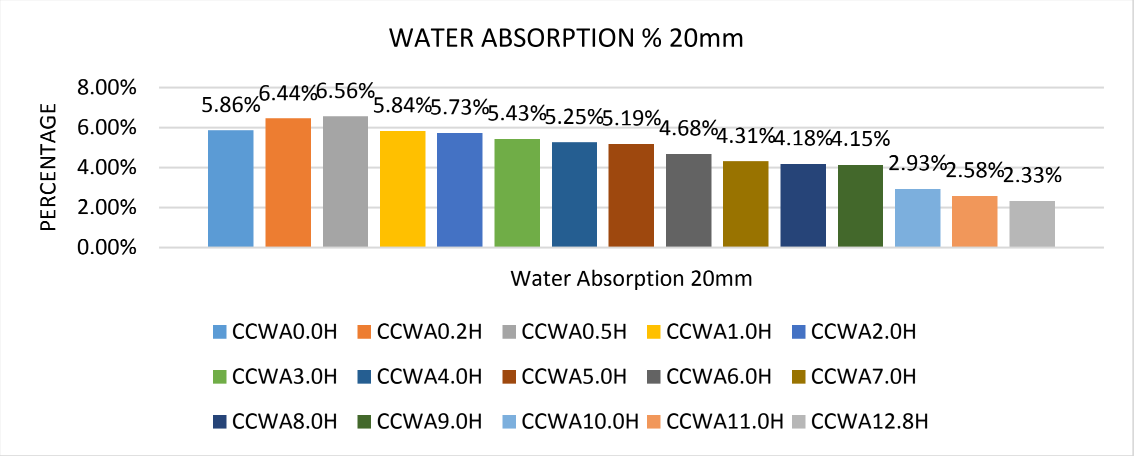


Fig. 9: Water Absorption % 20mm.

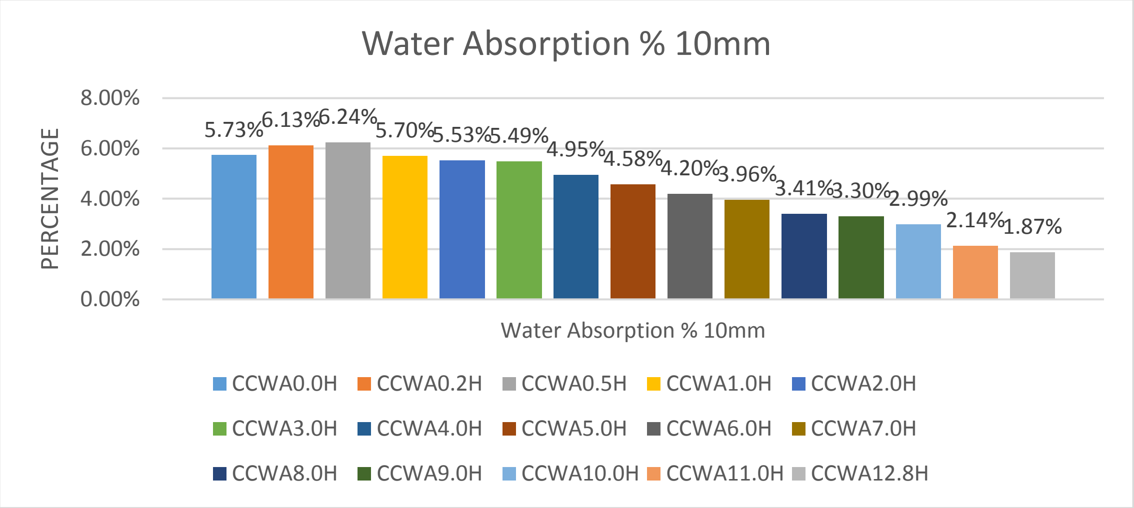


Fig. 10: Water Absorption % 10mm.

Fig 9 and Fig 10 show the experimental results of the water absorption conducted on 14 samples of CCWA treated with different HCl molarities and 1 sample of untreated CCWA. Unexpectedly, the untreated aggregate recorded less water absorption than those specimens treated with low HCl molarities 0.2 ml and 0.5 ml. Nevertheless, the untreated CCWA showed higher water absorption percentage compared with those treated with HCl molarity of 4 ml and higher. CCWA treated with HCl molarity of 0.2 ml and 0.5 ml showed higher water absorption. Thus, a low HCl molarity increased the porosity of the CCWA, which resulted in increased water absorption. Similar results have been reported by many researchers, that is, recycled aggregates have 3%–5% higher water absorption than NAs. When recycled aggregates are treated with pre-soaking in acidic solution, the water absorption indicates some improvement (Çakir, 2014; Çakır & Sofyanlı, 2014; Güneyisi et al., 2014; Kumar et al., 2012; Saravanakumar et al., 2016). However, the water absorption of treated recycled aggregates is higher than that of NAs because of the remaining mortar on the surface of the aggregates. However, using a high HCl concentration to treat the surface of the CCWA shows promising results. In the present work the CCWA treated with HCl molarity of 10 ml and above showed a similar water absorption to that of NAs.

3.3. The Microstructure surface of the CCWA

The microstructure surface of the CCWAs and the NA was obtained by a digital microscope. The Fig ures 11-26 below show the surface of NA, untreated CCWA, and treated CCWAs with different HCl molarities. The specimens treated with lower HCl molarity showed higher amounts of old mortar adhered to the surface of the aggregate than those treated with higher HCl molarity. The specimens treated with HCl molarity of 0.2 ml and 0.5 ml are shown in Fig 12 and Fig 13 respectively, Microcracks were observed on the old adhered mortar, which reasonably explained the low properties of the specimens treated with HCl molarities of 0.2 ml and 0.5 ml. Increasing the HCl molarity helped in further removing of the adhered mortar; the surface of all CCWA specimens indicated the removal of old mortar. Fig 25 and Fig 26 show that the CCWA treated with HCl molarity of 12.8 ml achieved a similar microstructure surface to the NA.

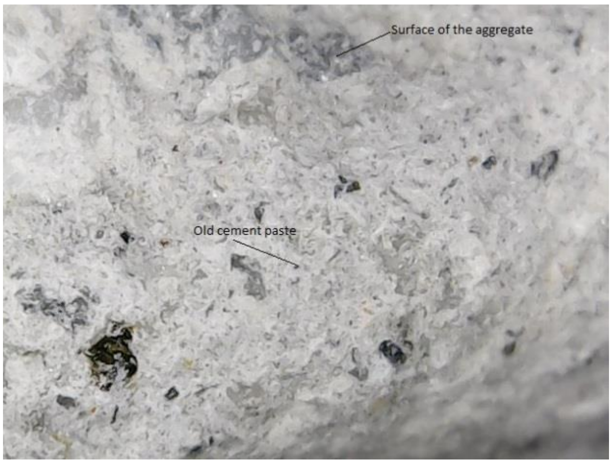


Fig. 11: The Microstructure Surface of the Untreated CCWA.

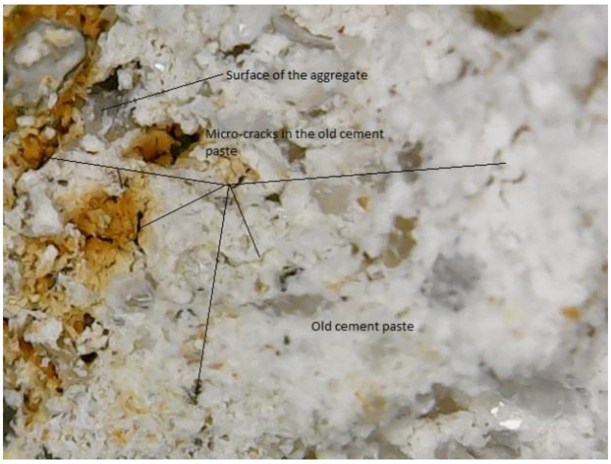


Fig 12: The Microstructure Surface of the Treated CCWA with HCL of 0.02 Ml.

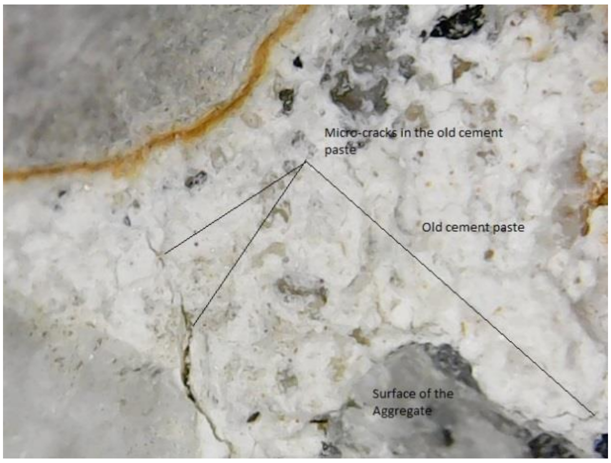


Fig. 13: The Microstructure Surface of the Treated CCWA with HCL of 0.05 Ml.

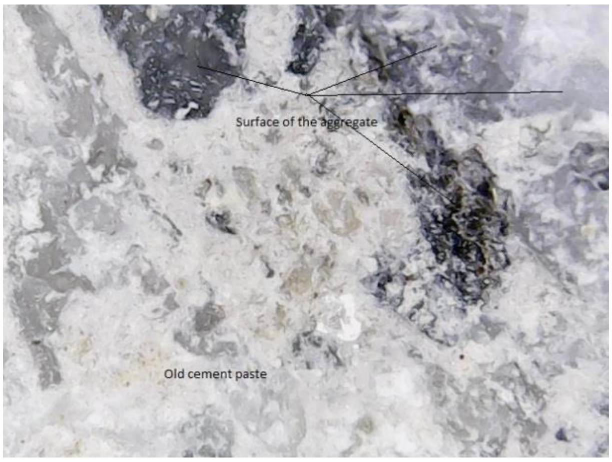


Fig. 14: The Microstructure Surface of the Treated CCWA with HCL of 1.0 Ml.

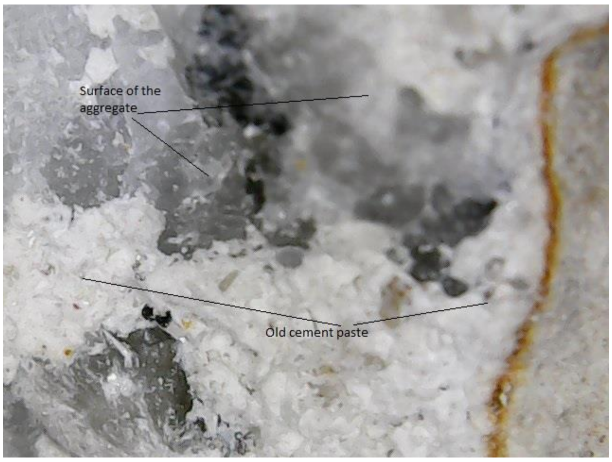


Fig. 15: The Microstructure Surface of the Treated CCWA with HCL of 2.0 Ml.

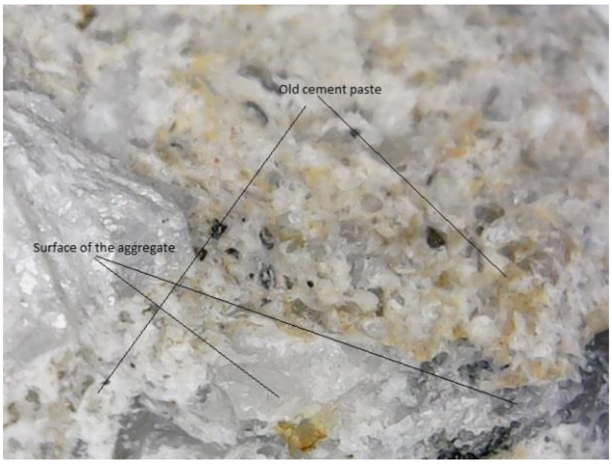


Fig. 16: The Microstructure Surface of the Treated CCWA with HCL of 3.0 Ml.

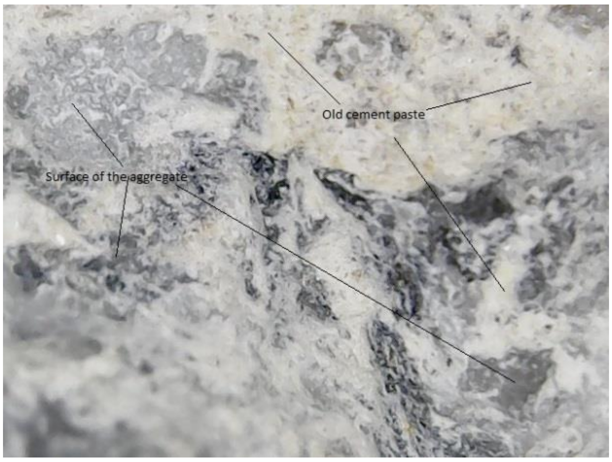


Fig. 17: The Microstructure Surface of the Treated CCWA with HCL of 4.0 Ml.

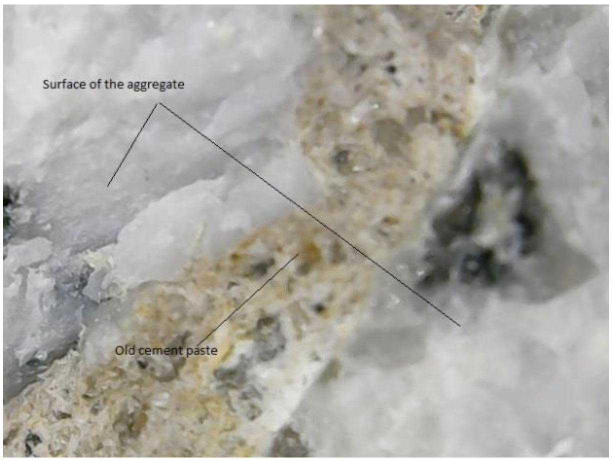


Fig. 18: The Microstructure Surface of the Treated CCWA with HCL of 5.0 Ml.

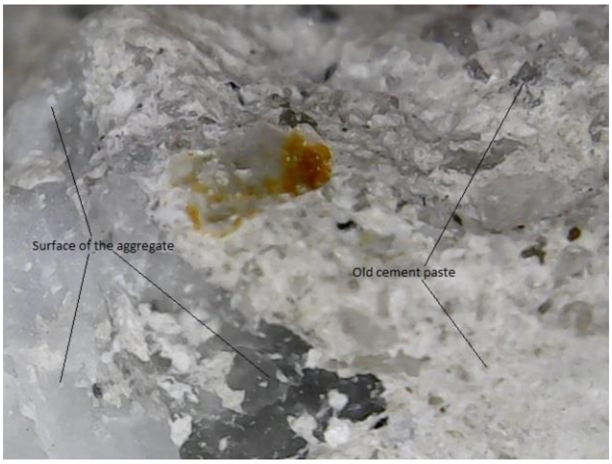


Fig. 19: The Microstructure Surface of the Treated CCWA with HCL of 6.0 Ml.

Fig. 20: The Microstructure Surface of the Treated CCWA with HCL of 7.0 Ml.

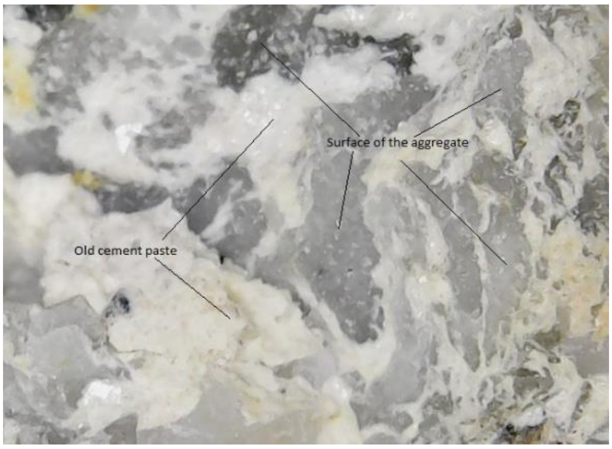


Fig. 21: The Microstructure Surface of the Treated CCWA with HCL of 8.0 Ml.

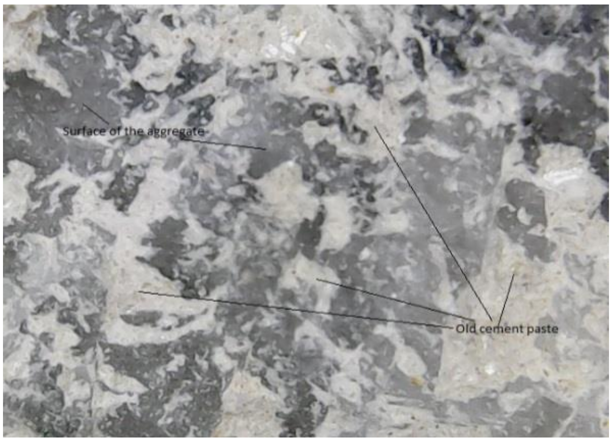


Fig. 22: The Microstructure Surface of the Treated CCWA with HCl of 9.0 ML.

Fig. 23: The Microstructure Surface of the Treated CCWA with HCL of 10.0 Ml.

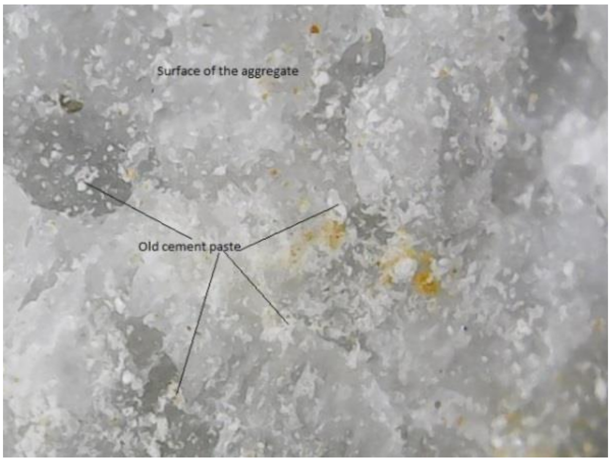


Fig. 24: The Microstructure Surface of the Treated CCWA with HCL of 11.0 Ml.

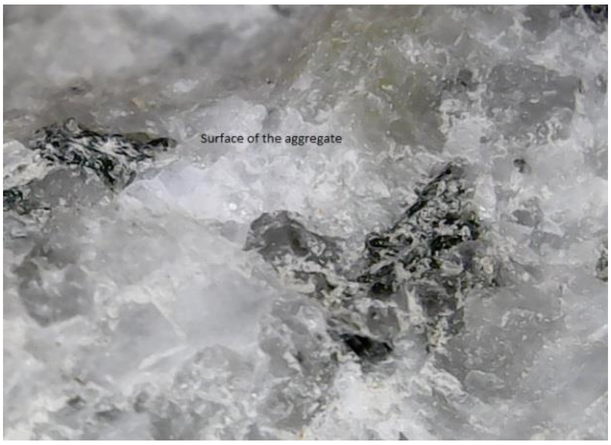


Fig. 25: The Microstructure Surface of the Treated CCWA with HCL of 12.8 Ml.

Fig. 26: The Microstructure surface of the Natural Aggregate.

3.4. The correlations matrix between variables

The interpretation of the strength of correlation was based on the description provided by Dudin (2013) The description is as follows:

- If r is +1, perfect positive correlation;
- If r is 0.7 - 0.9, strong positive correlation;
- If r near 0.5, moderate positive correlation;
- If r is 0.1 - 0.3, weak positive correlation;
- If r is 0, no correlation;
- If r is (-0.1) – (-0.3), weak negative correlation; and
- If r near (-0.5), moderate negative correlation;
- If r is (-0.7) – (-0.9), strong negative correlation; and
- If r is -1, perfect negative correlation;

Table 2 shows the correlation matrix between HCl molarity and the properties of treated CCWAs (that is, the ACV, AIV, and water absorption for 20 mm and 10 mm sizes). A significant correlation (as r = −0.644, −0.698, −0.684, and −0.712) occurs between HCl molarity and the ACV, AIV, and water absorption for 20 mm and 10 mm, with p < .01. Thus, a moderate negative association exists between HCl molarity and the properties of treated CCWAs. If HCl molarity increases, then the properties of the treated CCWAs improve. In other words, using a higher HCl molarity in treating CCWAs results in better quality of the CCWAs. A negative correlation also exists, such that if one factor decreases, then the other also decreases. The probability of this situation not being true is less than 1%; thus, over 99% of the time, this correlation is expected.

Table 2: Pearson Correlation between HCL's Molarity, Weight Loss and Properties of CCWA

	HCl Molarity	Aggregate Crush Value	Aggregate Impact Value	Water Absorption 20mm	Water Absorption 10mm
HCl Molarity	1				
Aggregate Crush Value	-.644**	1			
Aggregate Impact Value	-.698**	.984**	1		
Water Absorption 20mm	-.684**	.743**	.767**	1	
Water Absorption 10mm	-.712**	.765**	.789**	.987**	1

**. Correlation is significant at the 0.01 level (1-tailed).
Source: Computed Data Analysis

3.5. The relationship between the HCl's molarity and the properties of CCWA

Fig 27 and Fig 28 show the power relationship between HCl molarity and the ACV and AIV with R^2 = 0.981 and 0.987, respectively. While Fig 29 and Fig 30 show the linear relationship between HCl molarity and the water absorption of 10 mm and 20 mm of CCWA with R2 = 0.928 and 0.955, respectively. This relationship helps in predicting the values of ACV, AIV, and water absorption when the HCl molarity changes. With such values of R^2, the probability of this prediction not being true is less than 1%; thus, over 99% of the time, the prediction is likely to occur.

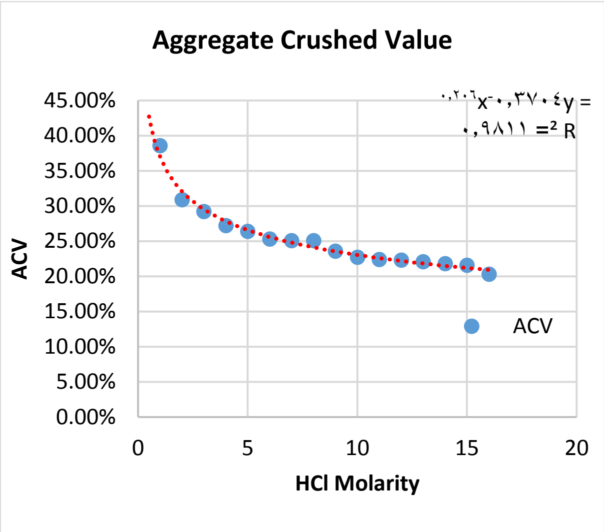


Fig. 27: The Relationship between the HCL Molarity and the Aggregate Crush Value.

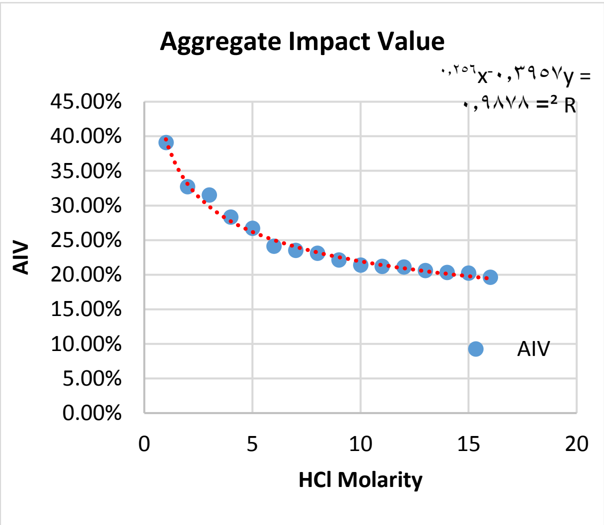


Fig. 28: The Relationship between the HCL Molarity and the Aggregate Impact Value.

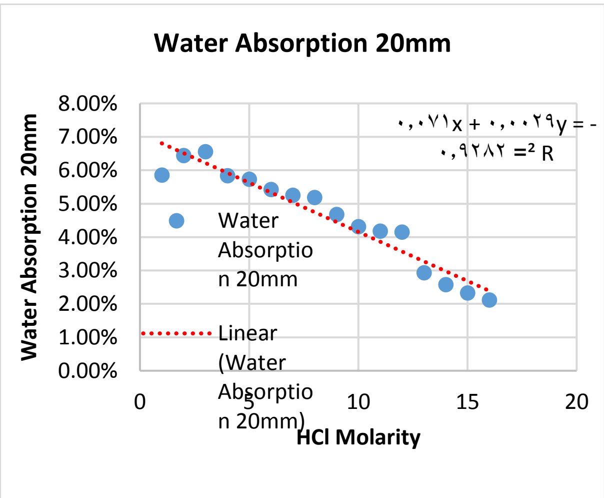


Fig. 29: The Relationship between the HCL Molarity and the Water Absorption 20 MM.

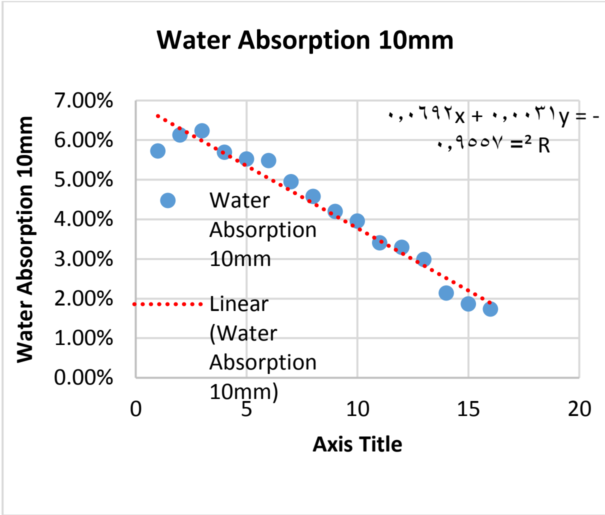


Fig. 30: The Relationship between the HCL Molarity and the Water Absorption 10 MM.

4. Conclusion

Using HCl to remove adhered mortar is effective, particularly when HCl with molarity of 10 ml or higher is used.
The size of CCWAs is an important factor in the treatment process; a smaller size of the CCWA indicates better result of the treatment.
In the experiment, using a low HCl molarity (0.2 ml and 0.5 ml) does not effectively improve the CCWA properties. Treating the CCWAs with lower HCl concentrations causes more microcracks on the old mortar adhered on the aggregate, thereby weakening the CCWA further.
CCWAs treated with HCl molarities of 10–12.8 ml exhibit similar properties to the NA. By contrast, CCWAs treated with low HCl molarities indicate inferior properties compared with the NA, which is caused by the old adhered mortar on the CCWAs.
The experiment shows a significant influence of the HCl molarity on CCWA properties; a linear relationship exists between HCl concentration and the ACV, AIV, and water absorption of CCWAs.

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