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Improvement of Engineering Properties of Recycled Concrete Aggregates Using Formic Acid

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ABSTRACT

It is observed that certain species of ants are capable of removing attached mortar from concrete, due to their ability to secrete formic acid (HCOOH), which was found to weaken the bond between the mortar and the aggregate. Formic acid is the simplest carboxylic acid and is readily available. Recycled Concrete Aggregates (RCAs) have inferior qualities compared with natural aggregates (NA), mainly attributed to the porous nature of the attached cement mortar. In this study, an environmentally friendly and a cost-effective method is attempted to treat RCAs to improve its engineering properties. In this method, RCAs were first soaked in a formic acid solution in which the formic acid reacts with cement hydration products attached to the surface of the RCAs. This reaction weakens the attached mortar which makes it possible to remove attached mortar from the RCAs by mechanical methods later. The treated RCAs have lower water absorption as there is less cement mortar attached. Tests were performed to distinguish between the mechanical properties of non-treated RCA and treated RCA. The paper discusses the results of water absorption, specific gravity and compressive strength of RCA and formic acid treated RCA. The results may help to improve the engineering properties of RCA and thereby increase recycling of construction and demolition waste that is usually dumped into landfills.

1. INTRODUCTION

Construction and Demolition (C&D) waste refer to the waste that is generated due to activities like construction, demolition, repair or renovation of various building structures. It generally consists of concrete, wood, gypsum, asbestos, metal, plastic, steel, and asphalt. Annually a total of 165-175 million tonnes of debris waste is generated in India [1], which is a serious concern due to the difficulties faced in safe disposal. In developing countries where infrastructural development is at its peak, the generation of such waste is bound to happen. The traditional form of disposal, i.e., dumping in landfills has shown to increase not only the construction cost due to transportation but also reduces the soil quality and causes air and water pollution. Concrete waste accounts for 30-40% of the debris produced [2]. Therefore, reuse of concrete debris is highly recommended, but their bulky, inert, heavy and nonuniform nature often adds to the difficulty of reusing and recycling. In concrete, reuse of aggregates is possible, but it comes with its own challenges. The recycled coarse aggregate has high porosity, high water absorption, low density and low specific gravity due to the mortar attached to it [3-8]. It leads to decrease in tensile, compressive and flexural strength of concrete. Many methodologies have been developed to improve the properties of recycled aggregates and thereby the engineering properties of concrete thus produced. The old mortar that is adhered to the aggregate surface is found to have minute pores and cracks that weaken the links in the microstructure of concrete [8]. A loose inter-transition zone is caused by high water absorption and porosity. Moreover, it results in the reduction of effective water content needed for hydration [9]. Therefore, the study on improving the quality of RCAs is significant, accounting to its cost-effectiveness, lower energy consumption, and resource optimization. Several surface treatments have been proposed to remove the mortar adhered to RCA. The use of mild acid was seen to effectively remove the mortar so as to increase the surface contact between aggregate and cement mortar. Tam *et al*. [9] studied the use of sulfuric acid (H_2SO_4), phosphoric acid (H_3PO_4), and hydrochloric acid (HCl) at various concentrations and soaking periods. It indicated a reduction in water absorption and rise in tensile and compressive strength as well as elastic modulus of the treated aggregates as compared to untreated aggregates. Liang wang *et al* [10] used acetic acid to remove the adhered mortar and an improved compressive strength was obtained. Acetic acid reacted with calcium hydroxide, calcium silicate hydrate and calcium carbonate in the cement mortar attached to the surface of the RCA. These reactions exhibited good removal of mortar from the RCA surface. Formic acid could serve as a good alternative to surface treatment acids due to its higher strength as compared to acetic acid as well as its cost-effectiveness and availability. The following are the relevant reactions (Eqs. (1) to (3)). In the present study, we intend to use formic acid for removal of the mortar from the surface and examine the change in specific gravity and water absorption of the treated aggregates which indicated the further improvement in the properties of concrete.

$$Ca[OH]_2 + 2\,HCOOH \rightarrow Ca^{2+} + 2HCOO^{-} + 2H_2O \qquad (1)$$

$$2CaCO_3 + HCOOH \rightarrow 2Ca^{2+} + 2\,HCOO^{-} + 2CO_2 \qquad (2)$$

$$C\text{-}S\text{-}H + CH_3COOH \rightarrow Ca^{2+} + CH3COO^{-} + H2O + SiO_2 \qquad (3)$$

Table-1

Composition of Cement

Material	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**K_2O**	**CaO**	**TiO_2**	**MnO**	**Fe_2O_3**
Cement	1.07	0.78	3.47	22.63	0.42	62.5	0.23	0.1	3.29

Table-2

Mix Design

Constituents	**Water**	**Cement**	**M-Sand**	**Coars Aggregate**
Proportions	140 liters	350 kg/m^3	779 kg/m^3	1272.4 kg/m^3

2. MATERIALS AND METHODOLOGY

2.1 Cement

OPC 53 grade cement was used which was available in the Concrete laboratory of VIT, Chennai. The chemical properties of cement used is given in Table 1.

2.2 Formic Acid

Formic acid is an organic acid naturally found in ants. Formic acid was supplied and manufactured by SRL chemicals, Chennai with the properties described in Table 3.

Table-3

Properties of Formic Acid

Chemical Formula	CH_2O_2
Molar Mass	46.03 g·mol^{-1}
Appearance	Colorless, Fuming
Density	1.220 g/ml
Melting Point	8.4 °C
Boiling Point	100.8 °C
Solubility in Water	Miscible

2.3 Aggregates

Natural aggregates were obtained from the concrete laboratory of VIT Chennai. The RCAs was obtained from the waste crushed concrete specimens from the same laboratory. The fine aggregate used was manufactured sand (m-sand) available in the same laboratory.

2.4 Treatment and characterizing of RCAs

The RCAs samples were first crushed and sieved using a 4.75 mm sieve to separate the fine and coarse RCAs. Three different formic acid concentrations were prepared (1%, 3%, and 5%) and an immersion time of 1day was used in this study. The variation of pH of the solutions was measured to monitor the reaction progression. After the immersion in acid for 1day,

the acid was decanted and the aggregates were soaked in water for 1day to neutralize any residual pH. The aggregates were

then oven dried at a temperature of 105 °C ± 5°C. The Water absorption and specific gravity of the RCA were then measured.

2.5 Water Absorption and Specific Gravity Tests

The Specific gravity and water absorption of the coarse RCAs and NA were measured as per provisions in IS 2386-1963 part 3.

2.6 Mix Design and Characterizing Specimens

Mix Design was prepared based on the Indian Standard (IS 456:2000). The mix design basis was for both RCAs and NA to obtain a Slump of 100 mm. A constant water-cement ratio of 0.45 was used. Table 2 represents the mix proportions of the concrete design. Concrete Specimens were cast into steel cubic molds of dimension 100 mm X 100 mm X 100 mm. The specimens were allowed to set for a period of 24 h at room temperature after which they were demolded and soaked in the curing tank. A total of 18 specimens were cast; 9 specimens to be tested after a curing period of 14 days and the remaining 9 specimens to be tested after a curing period of 28days. Out these 9 Specimens, 3 specimens were cast using NA, 3 specimens were cast using untreated RCA and the remaining were cast using treated RCA.

3. RESULTS AND DISCUSSION

3.1 Specific gravity and Water absorption

Table-5 shows the water absorption of normal aggregates (NA) whereas Table-6 shows water absorption of formic acid Treated Aggregates. The value of water absorption can be within the range of 0.5-2.5%, where 2.5% is the maximum permissible limit according to the IS456-2000. Tests performed on untreated RCA show the water absorption to be 3.09%. For the water absorption test, RCA was treated using 1%, 2%, and 3% formic acid solution. According to the results in Table 6, there was a decrease in water absorption by 15% after treatment using 1% formic acid solution. With 3% concentration, the decrease in water absorption was 22%. The reduction was increased to 36.5% when a 5% solution was used. This is attributed to the fact that more hydration products (same as Eq.(3)) i.e. adhered mortar, was dissolved by formic acid at higher concentrations. Hence the porosity of the treated RCA reduced with an increase in concentration. However, higher concentrations of formic acid may corrode the surface of the RCA which would increase porosity thereby increase water absorption.

Based on the figures 1 and 2 there is no clear trend that increased immersion may lead to further reduction in water absorption. This is due to the solution gaining a neutral pH after 24 hours of immersion, which is attributed to the fact that the Calcium Hydroxide present in the adhered mortar neutralizes the acidic solution (Eq.(1)), the acid also reacted with the free lime present in the mortar which lead ot the evolution of CO_2 (Eq.(2)). This suggests that one-day immersion is enough for efficient removal of mortar.

Table-4 shows that the specific gravity of NA is approximately 2.75, which complies with IS 456. The specific

gravity of RCA obtained from the laboratory was approximately 2.57. Treatment using 1% solution showed an increase of 2.33%. Treatment using 2% solution showed 3.5% increase in specific gravity. However, treatment with 5% solution showed similar results as 3% solution. This is because the adhered mortar increases the porosity which increases the volume which in turn decreases the density of the RCA hence the specific gravity is lowered.

Table-4

Specific Gravity of Aggregates

Type of Aggregate	Mean Specific Gravity	SD
Normal aggregate	2.753	0.05
RCA (Untreated)	2.57	0.015
RCA (1% Conc.)	2.636	0.03
RCA (3% Conc.)	2.66033	0.03
RCA (5% Conc.)	2.66066	0.02

Variation of pH 2-6 hrs

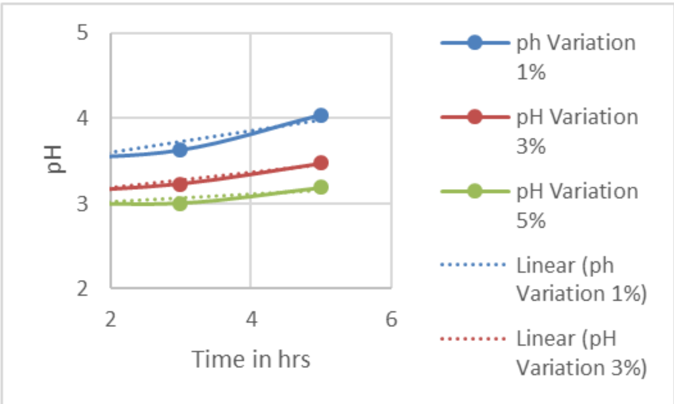

Figure 1

Variation of pH from 20-30 hrs.

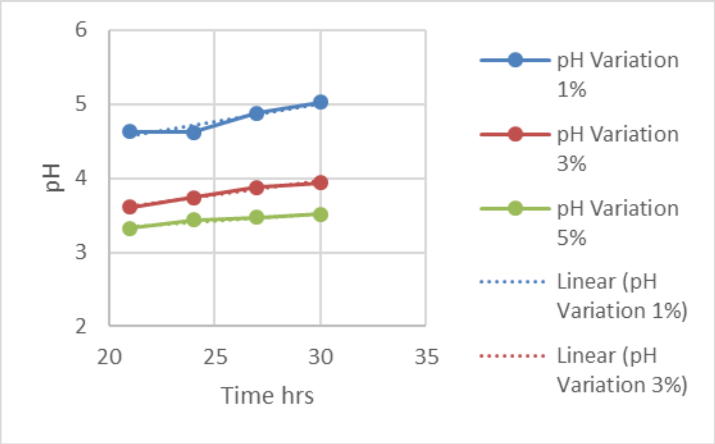

Figure2

Table-5

Water Absorption of NA

Aggregate	**Air Dry Weight(A)**	**Oven Dry Weight(B)**	**Water Absorption(%)**
NA Batch 1	1	0.995	0.5
NA Batch 2	1	0.995	0.5
NA Batch 3	1	1	0
		Average	0.333333333
		SD	0.288675135

Table-6

Water Absorption of treated RCA

Aggregate	**Water Absorption(%)**	**Avg**	**SD**
RCA Batch 1% -1	2.56	2.61	0.050163
RCA Batch 1%-2	2.617		
RCA Batch 1%-3	2.66		
RCA Batch 3% -1	2.04	2.41	0.340441
RCA Batch 3%-2	2.71		
RCA Batch 3%-3	2.48		
RCA Batch 5% -1	2.04	1.96	0.21166
RCA Batch 5%-2	1.72		
RCA Batch 5%-3	2.12		

Table-7

14-Day Compressive Strength

Aggregate Type	14-Day strength(Mpa)	Mean	SD
N.A	24.6	26.30	1.47
	27.1		
	27.2		
Untreated RCA	38.2	23.97	12.33
	16.4		
	17.3		
5% Treated RCA	32	36.50	3.91
	39		
	38.5		

Table-8

28-Day Compressive Strength

Aggregate Type	28-Day strength(Mpa)	Mean	SD
N.A	41.4	43.67	4.91
	40.3		
	49.3		
Untreated RCA	24.7	26.63	10.83
	16.9		
	38.3		
5% Treated RCA	33.9	37.37	3.13
	38.2		
	40		

3.2 Compressive Strength

From Table-4 and Table-6 we have observed that both 3% solution as well as 5% are effective in removing the adhered mortar(i.e.Decreased water absorption and increased specific gravity) but the 3% solution was less effective compared to the 5% solution in reducing the porosity of the aggregate as a result had a lower water absorption(i.e only a 22% decrease in water absorption in contrast to 36.5% decrease).Based on these obsrvations a 5% concentrated solution of Formic Acid was used to study the variations in compressive strength.Table-2 describes the mix design used in the study strictly according to

IS456:2000.Table-7 and Table-8 shows the compressive strength carried out after period of 14 days and 28 days respectively, theoretically the 14 day compressive strength should be 90% of the desired compressive strength (i.e for 30 Mpa it should be 27 Mpa),the results are divided into 3 types NA(Normal Aggregate),Untreated RCA(Recycled Concrete Aggregate and 5% treated RCA.The average compressive strength after 14 days for NA was 26.3 MPa which had a variation of 2.7% with respect to the theoreticalvalue, the average compressive strength of the untreated RCA samples was 23.97 MPa which had a 8.8% lower strength with respect to NA which mainly due to the presence of adhered mortar present on the aggregates which causes a non-uniformity in the ITZ which inturn accelerates the formation of microcracks and finally reduces the strength [8], the average compressive strength of 5% treated RCA was 36.5 MPa which was 34.32 % higher than Untreated RCA and 27 % higher than NA which is attributed to the formation of Calcium Formate which is an accelerating agent(i.e increases the early strength development of concrete) [11].The average compressive strength after 28-days for NA was 43.667 MPa which was 45% more than required(i.e 30 MPa) ,while the compressive strength achieved for Untreated RCA was 26.6 MPa which was 39 % Lower than NA and 11.33% lower than 30 MPa finally the average compressive strength for 5% treated RCA was 37.367 MPa which when compared with NA is 16.8 % lower but when compared with the required value 30 MPa it is 24.5% higher which is sufficient for construction purposes.

4. CONCLUSION

A cheap and effective method to treat RCA has been introduced. The proposed method of implementation has improved the quality of RCA. Formic acid treatment successfully removed the adhered mortar. Among present methods, this is a relatively cheaper and environmentally friendly approach. This study revealed that immersion of RCA in formic acid solution can successfully remove adhered mortar from the surface of RCA. Hence it improves the quality of RCA, such as water absorption and specific gravity. There is a possibility of Calcium formate to be produced as a by-product of the process which may be recycled as an accelerator in concrete instead of calcium chloride.

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