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Effect of Aggregate Types on Thermal Conductivity and Durability of Self-Compacting Concrete

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This study seeks to develop a sustainable, eco-friendly, self-compacting concrete (SCC) distinguished by its thermal insulation and durability, as these attributes have become essential for modern construction. For this purpose, four self-compacting concrete mixtures were prepared, made with four types of gravel where (natural gravel 100 % NA, recycled concrete gravel 100 % RA, and natural pozzolan gravel 100 % PZA, in addition to mixing 50 % PZA + 50 % RA) were adopted. This paper evaluated the capillary absorption, porosity, thermal conductivity, thermal diffusion capacity and durability of self-compacting concrete. Given the significance of examining the endurance of SCC in hostile settings, the mass loss following immersion in 5% hydrochloric acid and 5% sulfuric acid was also analyzed. The findings suggest the feasibility of utilizing 100 % PZA and a combination of 50% PZA with 50% RA to manufacture self-compacting concrete with thermal insulation and durability in hostile situations. The values of thermal conductivity reduction were 36.4 % and 16.4 %, respectively, and the mass loss reduction of the two mixtures towards chloric acid was 49.6 % and 36.8 %, and sulfuric acid was 83 % and 38.3 %, respectively.

Keywords: friendly self-compacting concrete, pozzolan aggregate, recycled concrete aggregate, thermal insulation, durability.

1. INTRODUCTION

In recent years, there has been growing concern about the environmental threats posed by the large quantities of waste resulting from building demolition operations, given the associated ecological impacts [1 – 3].

Thermal conductivity measurement is the best test to characterize the thermal conductivity capacity of a material [4, 5]. Other researchers found that thermal conductivity strongly affects conductive heat transfer through concrete [6]. However, replacing natural fine sand with fine aggregates enhances mortars' thermal properties [7]. The integration of nano-silica produces a decrease in heat conductivity, and the use of recycled lightweight particles improves the ultrasonic propagation speed of concrete [8, 9]. Thermal insulation properties are significantly improved by adding lightweight aggregates into cementitious mixtures [10 – 12].

Considering the significance of researching the durability of self-compacting concrete (SCC) in harsh conditions. According to [13], the addition of silica fume and metakaolin greatly reduces the chloride permeability of self-compacting concrete. Mixes prepared with cement containing high-volume fly ash were more resistant to chloride ion migration than control mixes [14]. According to [15], the presence of limestone fillers in SCC mixtures causes significant degradation during Mg_2SO_4 attack, particularly in the 30 MPa class. The combination of natural pozzolan, cement kiln dust, limestone powder, and crushed steel slag increases the strength of SCC [16]. However, fine aggregates FA could be replaced by recycled fine aggregates RFA, as long as the qualities of recycled aggregates RCA are considered in the mix design [17]. Other researchers discovered that using natural pozzolan PZ reduces the workability of SCC based on natural and recycled aggregates [18].

RCA harms the absorption during the manufacture of vibrated concrete [19]. A slight elevation in the water absorption of SCC was found when using a low amount of bonded mortar with coarse RCA [20]. At the same time, [21] confirms a direct proportionality between the amount of mortars and water absorption. Study mention that the number of multiple recycling of concrete increases the water absorption of SCC [22]. The results of [23] and [24] indicate that adding RCA was favorable for non-hydrophilic cement, creating microstructural barriers affecting permeability, water penetration, and sulfate attack. Concrete containing higher amounts of RCA and natural pozzolan demonstrated good results regarding chloride ion penetration and recorded lower apparent diffusion coefficient of chloride ions, and at the same time, SCC with PZ addition showed the lowest mass loss compared to the control concrete, which implies the beneficial use of RCA and PZ against H_2SO_4 attack [25]. Several researchers [26 – 29] concerning the effect of RCA on the physical properties of SCC, such as water absorption and permeability, show that RCA improves the behavior of SCC very remarkably. The joint use of fine RCA and metakaolin reduced the initial water absorption rate [30].

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[31] found that the addition of RCA lowers the electrical resistivity of SCC. The use of fine RCA increases the water absorption of concrete [32]. The higher percentage of substitution of RCA and fine aggregates in SCC increases carbonation depth [27, 31]. Authors [33] show that the existence of fibers in concrete mixtures does not affect the water absorption results. On the other hand, the increase in RCA with fibers decreases the resistance to the penetration of chloride ions in the concrete. They [34] highlighted the enhanced properties of SCC with the addition of M-sand, [35] discussed the cost reduction and improved durability of SCC with mineral additions, [36] demonstrated the effectiveness of high-performance SCC with electric arc furnace slag aggregates and cupola slag powder, which resulted in high-strength, low-permeability concretes.

This study seeks to assess the outcomes of an experimental investigation into the thermal and durability properties of SCC derived from diverse aggregate types. The objective is to address the significant depletion of natural resources, safeguard the environment from concrete waste, and simultaneously augment the value of well-bonded local materials, such as natural pozzolan aggregates.

2. MATERIALS AND MIXTURES

2.1. Cement

The cement used in all tests is CEM II/A-L42.5 Cement, whose chemical composition is illustrated in Table 1.

Table 1. Chemical composition of cement and pozzolan

Compound	SiO_2	CaO	Al_2O_3	Fe_2O_3	SO_3	LOI*	MgO
Cement	20.4	61.7	5.4	3	2.2	5	1.8
Pozzolan	43.5	10.5	17.2	9.5	0.9	2.6	2.98
*Loss of ignition							

2.2. Fine and coarse aggregates

Fig. 1 shows the appearance of the different aggregates: river sand (A), natural aggregates (B), recycled aggregates (C), and natural pozzolan (D). Table 2 summarizes the physical characteristics of the different aggregates. The chemical composition of natural pozzolan is summarized in Table 1.

Table 2. Physical and mechanical properties of aggregates

SiO_2	Sand	NA	RCA	PZA
Specific weight, kg/m^3	2.63	2.65	2.44	2.02
Bulk density, kg/m^3	1.54	1.3	1.22	0.86
Water absorption, %	3.1	1.6	6.7	13.95
Sand equivalent	89	–	–	–

2.3. Superplasticizer

The superplasticizer is "MEDAFLOW 30," derived from ether polycarboxylates and compliant with the EN 934-2 standard. It is a third-generation superplasticizer.

2.4. Mix proportion

The formulation we have adopted is based on the formulation proposed by the Japanese OKAMURA and called the general method, with some modifications concerning the selection of the quantity of sand in the mortar, the water/binder and the superplasticizer/binder ratio. Four (04) concrete mixes were prepared while keeping the water/cement ratio constant at 0.4. The concrete mix proportions are summarized in Table 3.

a

b

c

d

Fig. 1. Appearance of different aggregates

2.5. Experimental programs

After 28 days and according to ASTM D 5930 [37], thermal conductivity is the amount of heat that passes through a material of unit area and unit thickness in unit time when its two faces are different by unit temperature.

Table 3. Concrete mixture proportioning in 1m^3

Mix description	100 % NA	100 % RCA	100 % PZA	50 % RCA + 50 %PZA
Cement, kg	475	467	449	463
Sand, kg	886	871	837	864
NA 3/8, kg	277	–	–	–
NA 8/15, kg	553	–	–	–
RCA 3/8, kg	–	275	–	117
RCA 8/15, kg	–	550	–	253
PZA 3/8, kg	–	–	277	160
PZA 8/15, kg	–	–	553	300
SP, L	4.27	3.74	4.04	4.17
W/C, %	0.4	0.4	0.4	0.4

The corresponding heat transfer mode is thermal conduction Fig. 2.

Fig. 2. Thermal conductivity meter

Sorptivity measurement characterizes the absorption kinetics of materials. Sorptivity is expressed by the sorptivity coefficient (A) after 28 days, which was calculated according to equation (1):

$$A = \left[\frac{V}{S}\right] / \sqrt{t}, \tag{1}$$

where A is the sorptivity coefficient in cm/sec$^{0.5}$; V is the volume of water absorbed in cm^3; S is the surface in contact with water in cm^2; t is the elapsed time in seconds.

The specimens are preconditioned following the AFREM AFPC procedure (97) before the sorptivity measurements.

The calculation of open porosity established by equation (2):

$$P(\%) = \left[\frac{Vv}{Vt}\right] * 100 = \left(\frac{\frac{\Delta M}{S}}{\gamma\omega * L}\right) * 100, \tag{2}$$

where P is the open porosity, %; $\Delta M/S$ is the amount of water absorbed per unit surface, kg /m^2.h$^{0.5}$; γ_ω is the density of water is equivalent to 1000 kg/m^3; L is the frontal height of capillary imbibition (5 cm/ h$^{0.5}$= 0.050 m /h$^{0.5}$).

A measurement of the open porosity was taken at 28. After immersion in 5 % sulfuric acid (H_2SO_4) and hydrochloric acid (HCl) solutions, mass loss was measured at 1, 7, 14, 21, 28, 35 and 42 days of immersion following Eq. 3 according to ASTM C 267 [38], the acid solution is renewed according to the pH values ASTM C 192 [39].

$$\Delta C = \left[\frac{C0 - Ci}{C0}\right] * 100, \tag{3}$$

where ΔC is the change in mass, %; $C0$ is the weight of the sample just before acid treatment, g; Ci is the mass after (i) days post-attack (g) where i ranges from 1 to 42.

Digital photographs were taken for visual examination.

3. RESULTS AND DISCUSSION

3.1. Physical properties

3.1.1. Capillary absorption (sorptivity)

From Fig. 3, it is clear that the smallest value of the sorptivity coefficient is 5.73 × 10^{-4} cm/sec$^{0.5}$, corresponding to the mixture (100 % NA), and the largest value corresponds to (100 % PZA) of value 9.65 × 10^{-4} cm/sec$^{0.5}$ this phenomenon can be attributed to the elevated porosity of the natural pozzolan aggregates. Conversely, the findings indicate that (100 % RA) and (50 % RA + 50 % PZA) exhibit superior sorptivity values compared to (100 % NA), attributable to the cement paste enveloping the recycled aggregates and the elevated porosity of PZA; these results were found by [23, 24, 40]. On the other hand, there was more water uptake when more RCA was added [26].

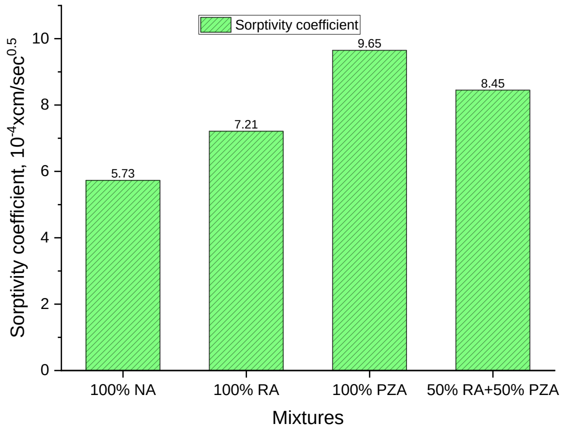

Fig. 3. Effect of different types of aggregates on the sorptivity coefficient

3.1.2. Open porosity

From Fig. 4, it is clear that the porosity has the same tendency as the sorptivity coefficient.

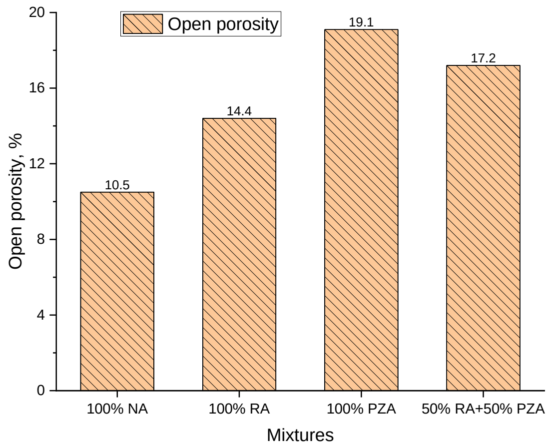

Fig. 4. Effect of different types of aggregates on the open porosity

In numbers, we have the following porosity results: 10.5, 14.4, 19.1 and 17.2 % for the mixtures 100 % NA, 100 % RA, 100 % PZA and 50 % PZA + 50 % RA, respectively. This is due to the high porosity of RA and PZA, as already explained in the absorption section above.

3.2. Thermal study

3.2.1. Thermal conductivity

The thermal conductivity is shown at the age of 28 days in Fig. 5. It can be concluded that the 100 % PZA mix records the lowest value of thermal conductivity (1.4 W/mK), followed by 1.84 W/mK, 2.2 W/mK and 2.47 W/mK for the 50 % PZA + 50 % RA, 100 % NA and 100 % RA mixes respectively. by comparing with the control concrete mix 100 % NA.

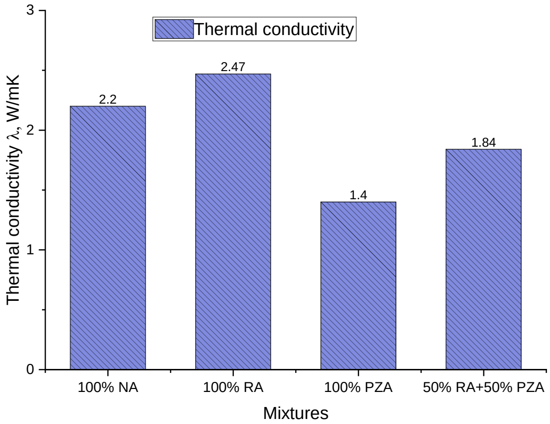

Fig. 5. Effect of different types of aggregates on the thermal conductivity

The 100 % PZA and 50 % PZA + 50 % RA mixes have undergone a reduction in the thermal conductivity of 36.4 % and 16.4 %, respectively, and this is due to the strong presence of pores, which play a great role in decreasing the thermal conductivity, which is consistent with [41], determined that thermal conductivity decreases by approximately 0.6 % for each 1 % increase in total porosity; this is logical since the pozzolan aggregates record a very high porosity compared to the other types of aggregates Fig. 4; this is consistent with the result of [40], and [42] who said that porosity is a key factor that affects heat conductivity.

3.2.2. Heat capacity

Fig. 6 indicates that the 100 % PZA mixture gives a better thermal insulation property than the control mixture, and its thermal property is connected to the capacity to absorb thermal energy. This finding enables us to infer that natural pozzolanic aggregates enhance the energy efficacy of concrete. This finding follows the findings of the research [6], which demonstrated that thermal conductivity substantially impacts conductive heat transfer in concrete. On the other hand, the same result was observed with the 50 % PZA + 50 % RA mixture, which also has an environmental satisfaction.

3.3. Durability study

3.3.1. Resistance to HCl attack

From the first day, mass loss begins for all self-placing concretes Fig. 7. This is explained by the high solubility of hydrochloric acid in water, which reacts quickly with calcium hydroxide $Ca(OH)_2$ according to the equation:

$$Ca(OH)_2 + 2HCl \rightarrow CaCl_2 + 2H_2O. \quad (4)$$

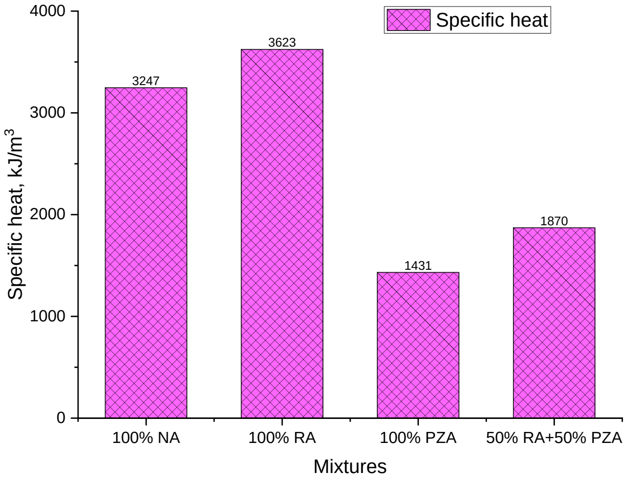

Fig. 6. Effect of different types of aggregates on the specific heat

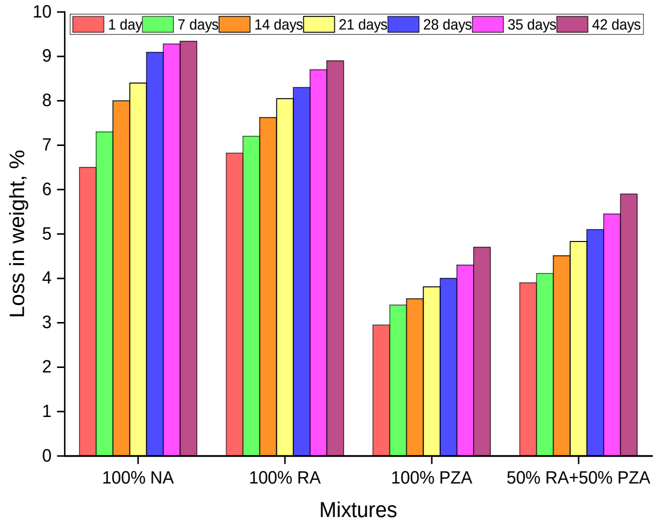

Fig. 7. Change in mass of mixtures versus the immersion duration for 5 % HCl

The highest mass loss is recorded for self-placing concrete based on 100 % NA, with a value of 9.34 % at 42 days, and the lowest mass loss recorded is that of self-placing concrete based on 100 % PZA with a value of 4.7 % at 42 days. For the mixture of 50 % PZA + 50 % RA, a mass loss of 5.9 % at 42 days is recorded. However, mineral additives to SCC can reduce costs and increase durability, as mentioned in [5]. This indicates the positive effect of using natural pozzolan aggregates and recycled aggregates against the attack of HCl acid with a rate of 49.6 % and 36.8 % for 100 % PZA and 50 % PZA + 50 % RA, respectively.

3.3.2. Resistance to H_2SO_4 attack

Mass loss was monitored during 6 weeks of immersion in a 5 % H_2SO_4 solution. The H_2SO_4 attack was performed according to the equation.

$$Ca(OH)_2 + H_2SO_4 \rightarrow CaSO_4 + 2H_2O. \quad (5)$$

From Fig. 8, we notice that all the mixtures have undergone an increase in mass loss with the duration of immersion. On the 1st day, the mixtures have undergone a small mass loss because sulfuric acid has a very low solubility in water, so it is relatively harmless.

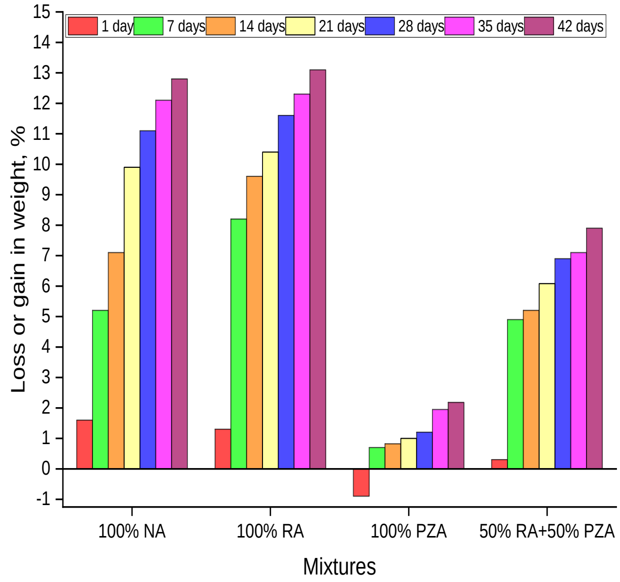

Fig. 8. Change in mass of mixtures versus the immersion duration for 5 % H_2SO_4

However, it is the sulfate ions that play, in this case, a harmful role. Exception: the 100 % PZA mixture recorded a slight gain in mass due to the low content of CaO in the pozzolan aggregates Table 1. The comparison between the mixtures at 42 days of immersion shows that the mass loss of 100 % PZA is less than 83 % compared to the control mixture (100 % NA), while [43], the total weight loss in OPC mortar was 75 % following 180 days of 3 % H_2SO_4 exposures. Reducing the overall weight loss in OPC is useless when the replacement amount of cement is thirty percent of natural pozzolana. On the other hand, the mass loss of the 50 % PZA + 50 % RA mixture is also less than 38.3 % compared to the 100 % NA mixture.

3.3.3. Visual examination

Fig. 9 and Fig. 10 depict the deterioration of the samples as a result of attack by hydrochloric acid and sulfuric acid, respectively, while Fig. 11 clearly compares the extent of damage to the samples as a result of their exposure to the two acids, confirming what was concluded in Fig. 7 and Fig. 8.

4. CONCLUSIONS

According to the experimental program, we can conclude, based on the results obtained:

1. The 100 % PZA and 50 % PZA + 50 % RA mixtures have the most significant absorption coefficient and open porosity values.
2. The 100 % PZA and 50 % PZA + 50 % RA mixtures record the lowest values of thermal conductivity 1.4 W/mK and 1.84 W/mK respectively. This indicates that they have good thermal insulation properties, which qualifies them for use in thermal insulation.

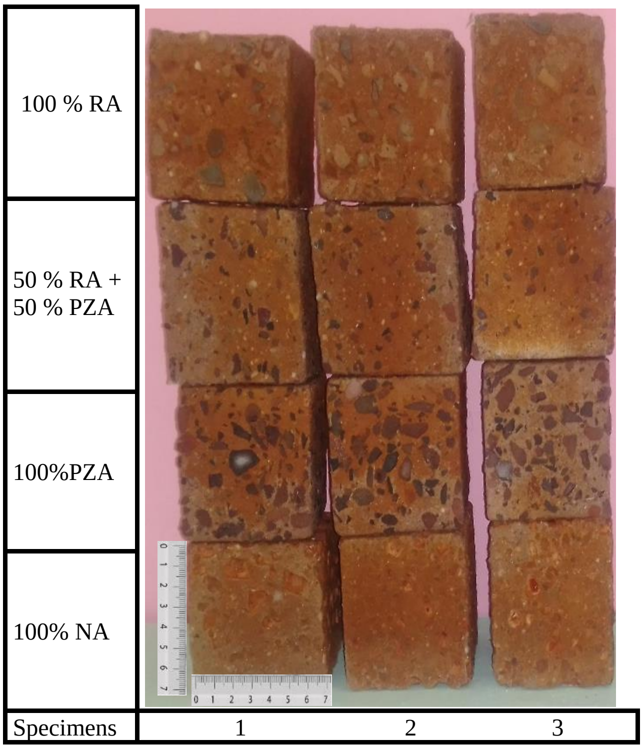

Fig. 9. Sample degradation of mixtures after 42 days of immersion in hydrochloric acid solution

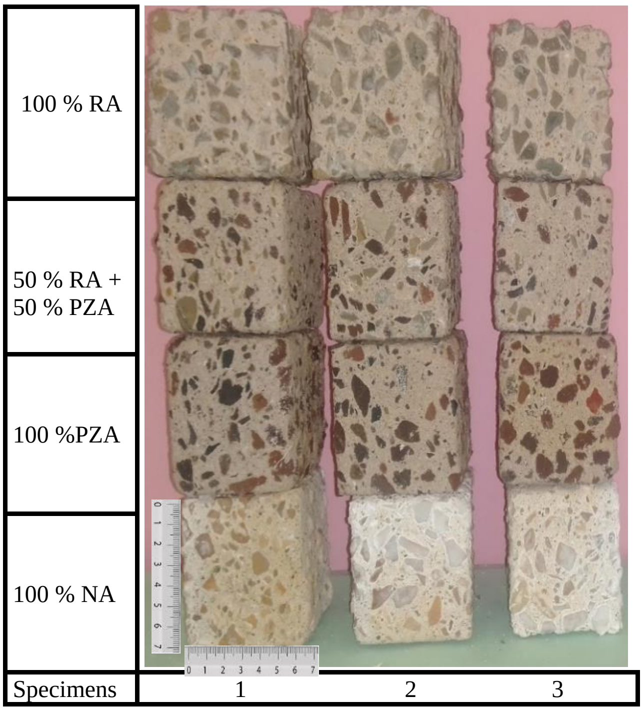

Fig. 10. Sample degradation of mixtures after 42 days of immersion in sulfuric acid solution

3. The incorporation of natural pozzolan aggregates and recycled aggregates favors resistance to assault by hydrochloric acid (HCl) and sulfuric acid H_2SO_4. The comparison between the different mixtures confirms that the mass loss decreases by 49.6 % and 36.8 % against the HCl attack and 83 % and 38.3 % against the H_2SO_4 attack for 100 % PZA and 50 % PZA + 50 % RA, respectively.

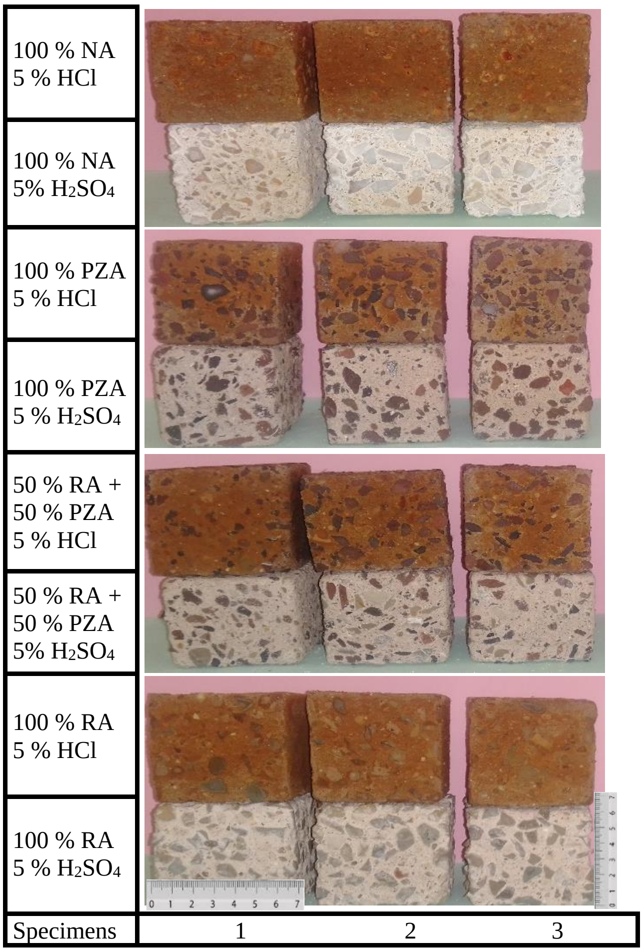

Fig. 11. Comparison of sample degradation of mixtures in hydrochloric and sulfuric acid solution

The primary objective of this research was to produce self-compacting concrete that is sustainable, insulating, and environmentally friendly. This has been achieved using 100 % natural pozzolanic aggregate or 50 % pozzolanic aggregate with 50 % recycled concrete aggregate. This has the potential to be applied in a variety of construction fields and to improve energy conservation. These mixtures can be used to build agricultural buildings like cold rooms for storing farm goods. When making walls, it's important to make sure they are insulated to keep heat from escaping. It is also suggested for use in the foundations of houses in aggressive environments.

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