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Effect of aggressive chemicals on durability and microstructure properties of concrete containing crushed new concrete aggregate and non-traditional supplementary cementitious materials

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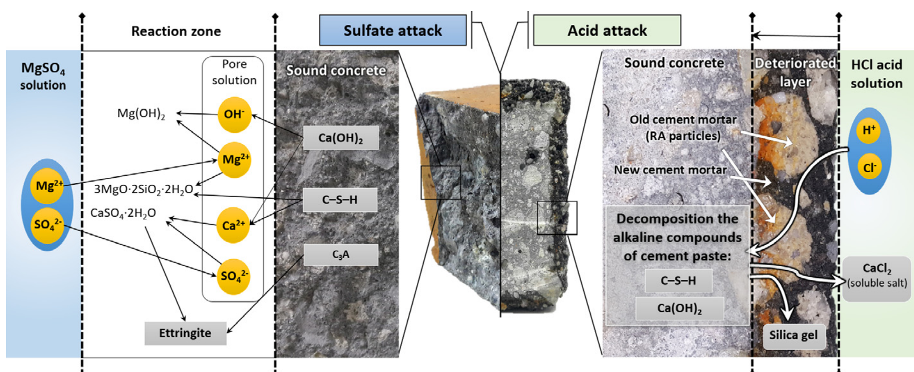
HIGHLIGHTS

- RHA, POFA and POCP were used as SCMs in concrete made of RA.
- The deterioration depth caused by acid was 2–4 times less for SCMs-based concrete.
- Less propagation of micro-cracks observed for SCMs-based concrete attacked by sulfate.
- The chemical compositions of concrete mixture is a significant factor affecting its performance.

GRAPHICAL ABSTRACT



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ABSTRACT

The increasing awareness and usage of traditional supplementary cementitious materials (SCMs) in concrete have pressured the construction industry to look for alternatives to overcome the concerns over their plentiful availability in the future. This research illustrates the performance of recycled aggregate concrete prepared with the incorporation of available industrial by-products, namely rice husk ash (RHA), palm oil fuel ash (POFA) and palm oil clinker powder (POCP) as alternatives for traditional SCMs. The effect of hydrochloric (HCl) acid and magnesium sulfate ($MgSO_4$) attack was evaluated by measuring the change in mass, compressive strength and microstructural analysis. The results revealed that the incorporation of RHA, POFA and POCP up to 30% minimizes concrete deterioration and loss in compressive strength when the specimens were exposed to HCl solution. In addition, the scanning electron microscopy image showed less propagation of micro-cracks caused by expansive ettringite in the case of $MgSO_4$ attack. Further, the X-ray diffraction analysis indicated that RHA is more effective as pozzolanic additive than POFA and POCP. Overall, the RA-based concrete had significant enhancement in its performance against acid and sulfate attacks using alternative SCMs from industrial by-products.

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1. Introduction

Durability and versatility of concrete have made it the world's most used construction material [1]. Consequently, the use of supplementary cementitious materials (SCMs) is becoming more extensive in the concrete industry due to their potential for improving long-term properties [2]. Typically, ordinary concrete contains about 10–15% cement and 60–80% aggregate by volume [3]. Taking into consideration a typical concrete mix proportions for the 3300 million tonnes of cement and the 22,000 million tonnes of aggregates consumed annually [4], the world produces 11,000 million cubic meters of ready mixed concrete, which makes concrete the largest consumer of natural resources. Recently, the utilization of recycled concrete aggregate (RA) from construction and demolition waste has attracted the attention of researchers as a sustainable and feasible material to replace the conventional aggregate in concrete [5]. Nevertheless, there is a consensus by researchers that the broad use of RA in concrete is hindered by its ability to withstand different aggressive environments, such as water absorbency, chemical attacks and exposure to seawater [6,7].

The relatively higher porosity of RA compared with normal aggregate makes the RA-based concrete more susceptible to damage when exposed to acid or sulfate solutions. The permeable voids found in the old mortar adhering on the RA particles allow the entry of acid ions, which in turn degrades the concrete and decreases its mechanical properties due to chemical reactions between acid ions and hydration products [8,9]. Moreover, these voids allow the ingress of sulfate ions to the pore structure and react with the hydration products to form gypsum and ettringite, which the latter is expansive in nature, leading to the deterioration of the concrete's surface [6,10]. Hence, the capability of concrete members to resist various aggressive environments is a key durability issue that affects the performance of concrete structures.

While the RA-based concrete in its beginnings only designed using conventional cement [11], later it was developed using blended cement with traditional SCMs including silica fume, fly ash and ground granulated blast slag to improve its mechanical and durability properties [12,13]. Furthermore, traditional SCMs have been utilized to develop self-consolidating concrete [4], fibre reinforced concrete [14], geopolymer concrete [15] and lightweight concrete [16,17]. Consequently, the practice of using SCMs is increasing, where more than 60% of ready-mixed concrete uses SCMs nowadays [18]. While concrete industry is expected to expand at a faster rate over time, the current trend involves using locally available industrial and agricultural waste ashes from the residues of rice and palm oil industries as alternative SCMs [19,20].

Rice husk ash (RHA) is about 18–22% by weight of rice husk after the combustion process in boilers at temperature of about 800–900 °C in biomass plants. RHA contains over 90% (up to 95%) amorphous silica, which enhances the pozzolanic reaction in mixtures containing Portland cement [21]. Chatveera and Lertwattanaruk (2011) [22] concluded that the durability of mortar exposed to acid attack was significantly improved when the cement was partially replaced by RHA, due to the improvement in the impermeability of the cement matrix.

Pam oil fuel ash (POFA) and palm oil clinker (POC) are by-products produced from different combustion processes of palm oil residues in a thermal power plant. POFA is the resulting ash after the combustion of these residues, and it is about 5% by weight of the original solids, while POC can be collected as large chunks after the burning process. The assessment of pozzolanic activity of POFA and palm oil clinker powder (POCP) confirmed that they are pozzolanic materials, since they have high amount of silica content (>60%) [23,24].

This research was conducted with the long-term aim of developing sustainable and high-quality materials for use as alternative SCMs. RHA, POFA and POCP were utilized as partial substitution of cement to determine the resistance of concrete made with 100% RA against aggressive chemical attacks. Previous investigations dealt with the effect of traditional SCMs, such as fly ash and silica fume on the durability properties of RA-based concrete [13,25,26]. In addition, there is limited research on the properties of RA-based concrete incorporating POFA [27], and there are no research works on the behavior of RA-based concrete containing RHA and POCP under chemical attacks. Therefore, the ability of RA-based concrete to withstand the natural aggressive environments was investigated using hydrochloric acid (HCl) and magnesium sulfate ($MgSO_4$) solutions. Moreover, microanalysis was considered, since the durability properties are related to the microstructure of concrete. The variables investigated in this research include the percentage of cement replacement by RHA, POFA and POCP (0%, 10%, 20%, and 30%), in addition to the whole replacement of conventional aggregate by RA. Further, the tests were conducted for a period up to 120 days, since the use of SCMs is commonly associated with concrete properties at later ages.

2. Materials and methods

2.1. Materials

2.1.1. Cement

A commercial ordinary Portland cement (OPC) with strength grade of 42.5 MPa conforming to ASTM C150 was used throughout this research.

2.1.2. Supplementary cementitious materials (SCMs)

Three types of industrial by-products were evaluated for use as SCMs, namely RHA, POFA and POCP. Both POFA and POC collected from palm oil mill were ground using Los Angeles abrasion machine, whilst RHA was purchased from supplier and directly used in the concrete. POFA was collected in the form of ash with relatively large particles, while large chunks of POC were collected with flaky, porous, and irregular shapes, and then crushed to smaller sizes. In order to improve the reactivity of POFA and POC, they were further ground using a Los Angeles abrasion machine with a speed of about 33 revolution per minute for 30,000 cycles to achieve a sufficient fineness and to match the requirements of ASTM C618. Fig. 1 shows the physical appearance of these SCMs compared with OPC. Their chemical and physical properties can be found in Table 1. It can be seen that the properties of RHA, POFA, and POCP conform to the requirements of ASTM C618 for use as SCMs.

The scanning electron microscopy (SEM) image of the particle shape and surface texture of OPC, RHA, POFA and POCP are illustrated in Fig. 2. It can be seen that the particles of OPC are solid and spherical in some cases. On the other hand, the particles of RHA, POFA and POCP are irregular. Furthermore, it is obvious from the images that the outer surface of the POFA is porous, while the surfaces of RHA and POCP are made up of sharp edges.

The particle size distribution of the binding materials is presented in Fig. 3. It can be clearly seen from the curves that RHA and POFA have similar fineness of OPC, while POCP is relatively coarser.

2.1.3. Aggregates

Local mining sand with maximum size of 4.75 mm was used as fine aggregate in all mixes. Fig. 4 shows the normal aggregate (NA) and RA with a maximum size of 20 mm that used as coarse aggregates. All aggregates were used at air dried condition. The moisture content of sand, NA and RA was 0.87%, 0.15% and 2.36% respectively. Moreover, the specific gravity, compacted bulk density and water absorption of NA and RA were found as 2.60 and 2.31, 1481 and 1370 kg/m^3, and 0.77% and 4.76%, respectively. Since this research focuses on the effect of SCMs on RA-based concrete, the RA was extracted from old concrete specimens that has consistent characteristics to minimize the potential effect of impurities on the new concrete. In addition, the quality of demolished structures varies in a wide range due to the different compressive strengths of the structures, and hence, the compressive strength of those old specimens used in this research was known and this would minimize the number of variables. Therefore, the RA was extracted from old concrete cubes, cylinders, prisms, and reinforced beams that have been produced using conventional materials. The compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity of the old (parent) concrete were 51.7, 4.16, 4.90 and 34120 MPa, respectively.