Performance of Recycled PVC Aggregates in Concrete – Comparative Study

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ABSTRACT

Plastic is the most used material in the world due to its easiest manufacturing and shaping, low density, and low cost. Their accumulation poses environmental problems due to no biodegradable. In recent times, researchers have concerned with the reuse of waste and recycled plastic materials in the concrete mix. Many studies have been published for the behavior of concrete having recycled plastic materials. This paper summarizes and compares the published literature studies on PVC recycled as a partial fine and coarse aggregate form replacement in concrete. The characteristics of the material, size and shape, replacement ratio, and the influence of PVC materials on the concrete properties have been discussed. The resultant concrete properties such as slump and workability, density, compressive strength, and durability of the PVC concrete were compared in the available literature. The results are not convergent due to many factors such as replacement of PVC ratio, shape, size, and the case of the PVC waste. In general, concrete containing PVC reduces the density, mechanical properties (compressive strength, splitting tensile strength, and flexural strength), and dry shrinkage as the PVC replacement ratio increase. The lower mechanical strength of concrete may be attributed to weak of ITZ in the interface between the aggregates and cement paste. Resistance of chloride ion penetration is better in PVC mixed concrete than the reference concrete. The PVC concrete may classify the lightweight based on the density of the concrete.

Keywords: Recycled plastic, PVC plastic, PVC Concrete properties.

1. Introduction

The polymer products are widely used in every field, especially in packaging, industries, agriculture, and others. In the last half of the 20th century, plastics have been used increasingly in a broad range of products because of ease of design and manufacture, and cheaper cost. Over 275 million metric tons (MT) of plastic waste in 2010 were produced in 192 coastal countries, and from 4.8 to 12.7 million MT may enter the ocean [1]. In 2017, the production of the plastic has grown to 348 MT [2]. The produced from raw materials was 360 in addition to 30 MT from recycled according to a pilot study of six associations and organizations concerned in the plastics in 2018 [3]. Although of substantial amounts of plastic production, the recycling of the waste presents only one-third of the waste while its quarter goes to landfill, and the rest for energy recovery [4]. The amount of recycled plastic waste was doubled from 2006 to 2018.

Polyvinyl chloride (PVC) is one of the plastic types uses in the construction such as windows, frames, profiles, floor, and wall coverings, pipes, cable insulation, garden hoses, inflatable pools, etc. The first discovery of PVC was in 1835 by the French physicist Victor Regnault and developed manufacturing processes enabling its industrial progress after that by the German professor Fritz Klatte in 1912 [2]. By polymer types in 2016, the PVC presents 10 % of the European plastics converter demand [4]. PVC recycled has been partially replaced in concrete as a fine or coarse aggregate over the past few decades. This article summarizes some related studies of PVC recycled waste materials in concrete and supplies a space for details by comparing the results effect of the PVC additive in concrete from these studies.

2. Material properties of PVC plastics used in concrete

Polyvinyl chloride (PVC) is a basic element in engineering construction and supplies a series of services such as all types of pipes for fluids and gas distribution, doors and windows, profiles, floor and wall coverings, pools, etc. The ground PVC scrap works well as a partial substitute for concrete aggregate rather than being sent to landfill or incinerated. The PVC is replaced in concrete as a part of fine or coarse natural aggregates. Using recycled plastic in concrete reduces the weight of concrete, thus reducing transportation costs [5]. Because the properties of bulk density, compressive and tensile strength of concrete containing waste plastic in general or PVC in any form are less than conventional concretes, the plastic concrete can be used as lightweight concretes for structures with lower strength requirements [6, 7, 8]. Significant differences in properties can occur, based on the source of the waste and whether is mono/a mixed plastic, is the plastic clean from the inorganic components, and are the composing polymers and their respective ratios in the mix is a known [9]. In general, the plastics in concrete have good characteristics as insulation for hot, cold, sound, and saving energy [10]. The chloride ions resistance in the structure is influenced by PVC aggregate, and the results show that the PVC aggregate can be added to the concrete exposed to the aggressive environment [11].

3. PVC Plastic aggregates

There is no specific standard classify the granule size of the plastic added to the concrete or replacement ratio. The PVC recycled concrete may be divided according to the size of the plastic added into dust particles with a size less than 1 mm, fine aggregate with a size of 1-4 mm, and with a size of more than 4 mm for coarse. Radimir et al [6] summarized the classification of the form into dust particles with a size up to 1 mm, for flakes with a size of 1-10 mm, pellets with a size of 10-25 mm and length 25-50 mm for fibers. Figure 1 shows the variety of forms of PVC aggregates used by the researchers. PVC collected directly from the waste PVC pipe by crashing typically has an angular and rough surface [11, 12, 13]. Some PVC aggregates are also processed from the waste by melting and have a smooth surface as seen in Figure 1d. Numerous publications have concerned the properties of concrete containing PVC recycled as aggregate in different forms and sizes.

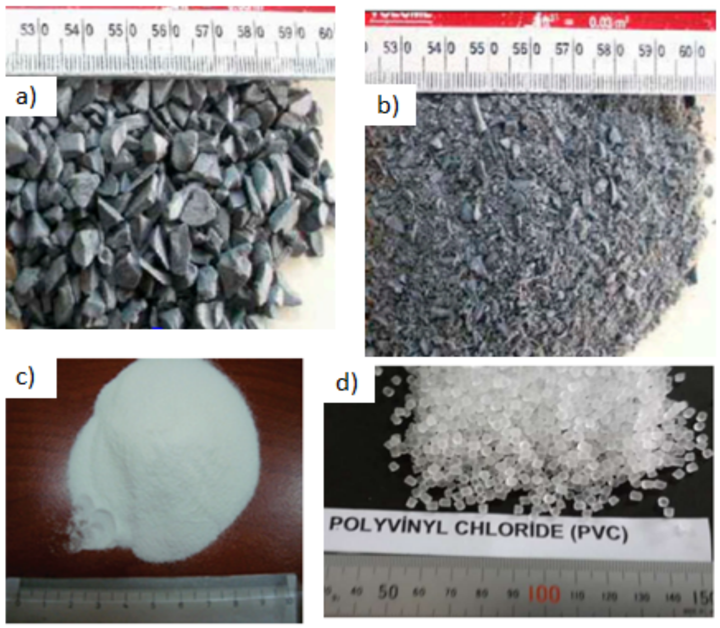

Figure 1: *Different forms of PVC aggregates used in concrete such as (a) coarse aggregates, (b) fine aggregates, (c) fine powders and (d) processed PVC aggregates [11, 12, 13].*

4. Properties of concrete containing PVC aggregates

This section integrates the information on various fresh, mechanical, and durability properties of concrete mixed with PVC aggregates in the available researches.

4.1 Fresh properties of PVC mixed concrete

Concrete is a type of material that can be poured into the mold to create any shape. However, the fresh properties of concrete such as workability, yield stress, viscosity, consistency, plastic shrinkage, etc. are the crucial factors that can influence both the mechanical and durability properties of hardened concrete [14]. The air content, bleeding, and segregation of fresh concrete are also crucial factors that need to control for having the maximum benefits of using concrete.

In a study [12], PVC was used as both powder (size is between 0 and 0.25 mm) and fine (size is between 2 and 4 mm) forms at 10, 20, and 30% replacement level by volume of aggregate in concrete. The slump value of the concrete was reduced for both powder and fine form of PVC. The maximum reduction of the slump was noticed by about 17% when 10% of PVC fine replaced by the aggregates. However, this reduction was reduced as the percentages of PVC were increased. At 30% replacement of PVC, the slump value was as same as the reference concrete. This trend of a similar slump or even slightly higher slump in concrete was also noticed for the coarse (size > 4 mm) PVC at a higher level of percentages (30, 35, and 40%) [13]. Because of the non-absorbent nature of PVC, the concrete mix may have more water and thus higher slump can be achieved. This behavior was opposite where a systematic reduction in the slump value of concrete was reported for an increased amount of PVC fine aggregates in concrete [15]. Najjar et al. [16] investigated the effect of the percentage of rigid PVC with a particle size of about 4 mm on the slump also. The result showed that there is an increase in the value of slump about 17%, 33%, and 87% in concrete at the PVC waste ratios of 5%, 10%, and 20%, respectively compared with the reference concrete mix.

Azad et al. [17] find that the slump was not changed when fine aggregate is replaced with PVC aggregate not more than 15%, and with coarse aggregate replaced by up to 30% PVC aggregate. Sudden changes in slump value when PVC coarse aggregate increased to 45% and PVC fine aggregate to 65%.Overall, the slump value of concrete depends on the shape of the PVC aggregates. The smooth shape of processed PVC granule aggregates may lead to a higher slump of concrete, while the angular shape of PVC aggregates increases the friction between the aggregates particles and thus reduce can reduce the slump. Slump value was gradually reduced even at a lower level of PVC replacement (2.5, 5, 7.5, 10, 12.5, and 15%) as fine aggregates in concrete [18]. At these levels, the slump values decreased by about 4%, 6%, 11%, 12%, 15%, and 18%, respectively, in comparison to the reference concrete. Figure 2 shows the workability of PVC mixed concrete reported by the researchers in the existing literature [15, 19, 20]. Inconsistency of the slump results can also be seen from the figure. The density of fresh concrete also decreased as the percentages of PVC aggregates increased [12, 13, 18]. Maximum 6% and 10% reduction in density were reported for the PVC replacement of 30% and 40%, respectively[13]. The lower density of PVC mixed concrete can be attributed to its lower compaction factor as reported in [21]. The air content of concrete was found to be increased with the creased percentages of PVC aggregates [22].

For the PVC replacement levels of 10, 20, 30, 50, and 100%, the air content in concrete was increased to 10%, 10%, 110%, 167%, and 386%, respectively, when compared with the reference concrete.

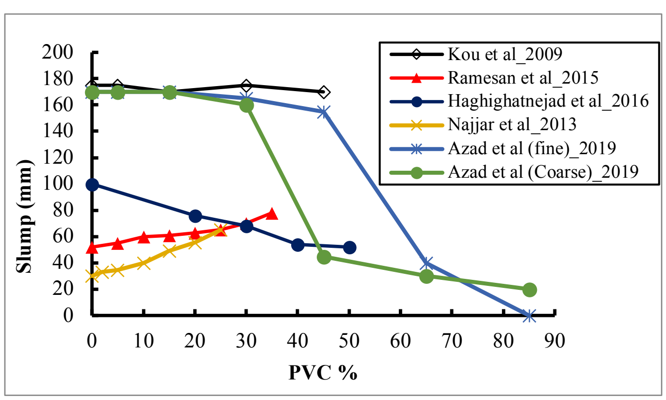

Figure 2:*Slump value of concrete with different percentages of PVC.*

4.2 Hardened properties of PVC mixed concrete

Concrete ability to withstand the structural and service loads is defined by its hardened properties. The hardened properties such as dry density, compressive strength, tensile strength, modulus of elasticity, etc. were investigated in researches [11, 13, 16, 17, 19, 23]. Results obtained by Hussein et al[18]show that 15% of fine PVC replaced in concrete mix can be reduced the dry density of reference concrete (2331kg/m^3) to (1892kg/m^3), which mean this density is in between the limitation of lightweight structural concrete density according to (ACI 213R 2014) [24]. Different results by Azad et al. [17], where the significant change in density of concrete with PVC aggregate at high PVC content of 85%. Even at this content of PVC replacement, the concrete became lightweight only when the coarse PVC Aggregatewas replaced. This may be attributed to the relatively high-density of PVC aggregate used in this study in comparison with that used by the last investigation. The dry density of the concrete decreases by 2.00%, 3.20%, and 4.73% for the concrete containing 10%, 20%, and 25% PVC waste aggregate, respectively in a study by Najjar et al. [16]. The reduction in the dry density is attributed to the PVC density is lower than the natural aggregate density.

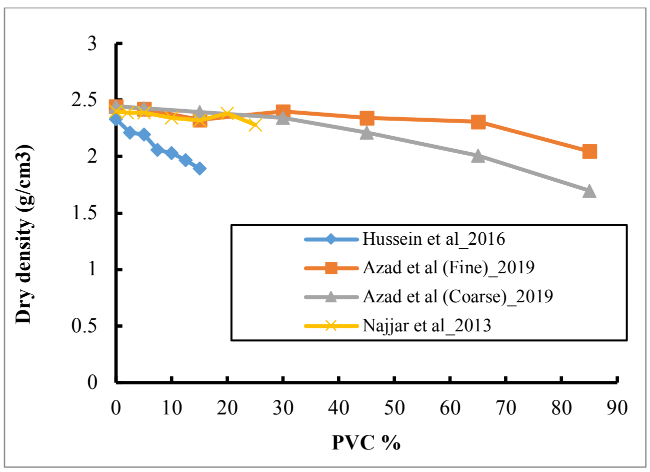

Figure 3: *Effect of PVC replacement on the dry density of concrete of PVC.*

In every research, it was found that the partial replacement of natural aggregates by PVC aggregates reduced the compressive strength of concrete at any remedial age. At 28 days, the compressive strength of concrete with 20, 30, 40 and 50% PVC fine aggregate mixed concrete was about 10%, 13%, 18%, and 34% lower than that of the control mix [23]. In another study [19], 28 days compressive strength of concrete with the inclusion of PVC granule at replacement level of 5, 15, 30, and 45% reduced about 9%, 19%, 22%, and 47%. The difference in concrete strength was attributed to the weak bond strength between the PVC aggregates and the cement paste. The lower elastic modulus of PVC aggregates compared to the cement paste also form cracks around the PVC particles and hence lower the compressive strength [19]. When comparing the PVC in powder and granule form, the strength of powder

PVC concrete was lower than the concrete with granule PVC[12]. Research also showed that the surface treatment of plastic aggregates by chemicals such as hydrogen peroxide solution (H_2O_2) and calcium hypochlorite solution ($Ca(CO)_2$) can improve the mechanical properties of concrete [25]. Chemical treatment reduces the hydrophobicity of the surface of the plastic surface, allows a stronger bond to be formed between the cement paste and plastic. Figure 3 shows the compressive strength of concrete at 28 days with different percentages of PVC found by the different researchers. In all studies, compressive strength was found to be decreased as the PVC content increased. Although the compressive strength of concrete is reduced as the percentages of PVC content increased, however, 10% PVC replacement was found to be acceptable as the overall strength reduction was below 10%, which is still acceptable for many applications.

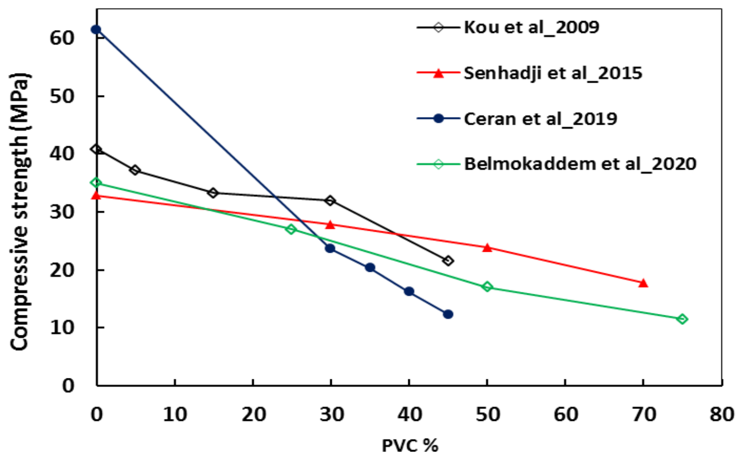

Figure 4: *28 days compressive strength of concrete with different percentages of PVC aggregates.*

Like the compressive strength, the modulus of elasticity of concrete was also reduced as the percentages of PVC content increased. At 28 days, about 7%, 14%, 19%, and 62% lower modulus of elasticity was found in concrete with PVC replacement of 5, 15, 30, and 45% [19]. In another study where 30 and 45% natural aggregates were replaced by the PVC aggregates, a maximum reduction in modulus of elasticity was reported to be 8% and 32%, respectively [13]. The splitting tensile strength of concrete was also found to be decreased as the PVC content in the mixes increased[19, 26]. For 10, 20, and 30% of PVC replacement in concrete, at 28 days, the splitting strength of concrete was reduced to about 24%, 30%, and 34% [26]. Lower flexural and tensile strength of different percentages of PVC mixed concrete was also found in [18]. On the contrary, almost similar flexural and tensile strengths were reported for various percentages of PVC dust mixed concrete [27].

From the above discussion, different researches have concluded the different range of optimum PVC content as well as its impact on the concrete properties. Nevertheless, the variation in the results of different studies can be attributed to their different remedial conditions, water-cement ratio (w/c), physical properties of PVC and concrete mix compositions.

4.3 Durability properties of PVC mixed concrete

In its total service life, concrete structures undergo various kinds of environmental loads or actions. The durability of concrete defines by its ability to sustain in those environmental actions without any major damages. This section aims to summarize the different durability tests performed on PVC mixed concrete in the existing researches.

Chloride ion penetrability in different percentages of PVC mixed concrete was investigated by Kou et al [19]. It was found the resistance in chloride ion penetration of concrete increased as the percentages of PVC content increased. Concrete specimens after curing of 28 days showed that the total charges (coulombs) passed through 5, 15, 30, and 45% PVC mixed concrete were reduced by about 12%, 19%, 27%, and 36%, respectively, in comparing to the control concrete specimens. The resistant nature of PVC aggregates can block the passage of the chloride ion and thus increase the durability of concrete.

The water absorption in PVC mixed concrete was also investigated in [15]. For this purpose, cube specimens (100 mm) were dried in the oven and then submerged in tap water. The weight gain was measured at a regular interval. Concrete specimens with the inclusion of 20, 30, 40, and 50% PVC aggregates showed lower absorption of water than the control specimens. The inclusion of different percentages of PVC specimens showed the final absorption values of about 55%, 47%, 35%, and 70% lower than the concrete specimens.

The different percentages of PVC mixed concrete specimens were also tested in ultrasonic pulse velocity (UPV) [17]. At lower percentages of PVC (5% and 10%), there was no noticeable difference in the results of PVC concrete specimens when compared with reference specimens. However, at 40% PVC replacement level, the reduction of UPV values was about 13%, 13%, and 14% for concrete ages of 7, 28, and 56 days, respectively. Therefore, at a lower level of PVC replacement in concrete, the effect on residual UPV was not found to be significant. It was concluded that the similarity of concrete mix improves when adding PVC aggregates which can lead to reduce the permeable pores in the matrix and improve the UPV [12].In another study, it was concluded that the concrete with 50% PVC, the UPV value is still at good range and acceptable for many applications [11].

The rate of drying shrinkage of concrete also decreased as the percentages of PVC aggregates increased [19, 28]. Figure 4 shows the drying shrinkage results at 60 days of PVC mixed concrete found in existing studies [19, 28]. Water loss from the concrete induces capillary tension force and thus drying shrinkage occurs in concrete. The intensity of this capillary tension depends on the pore volume, size, and structure of the concrete [29]. Since PVC is resistant and does not absorb water when compared to natural aggregate and hence would be able to reduce the overall drying shrinkage [19].

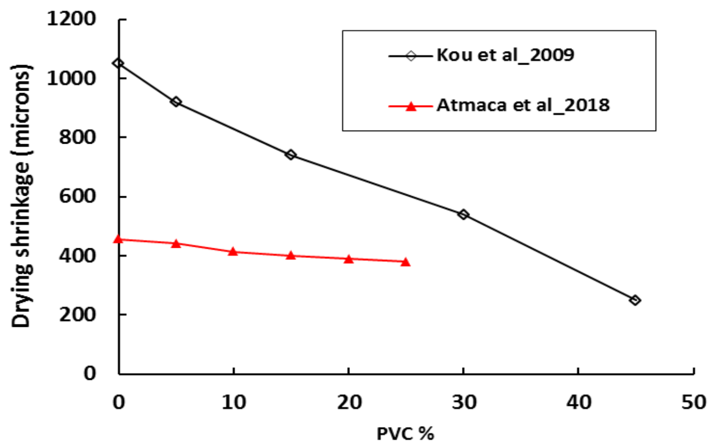

Figure 5: *Drying shrinkage of PVC mixed concrete at the age of 60 days* [19, 28].

Microstructures of PVC mixed concrete

The effect of PVC on the microstructure of cement paste was also invested through a scanning electron microscope (SEM) image analysis [11, 17]. As shown in Figure 6a, a weak interfacial transition zone (ITZ) forms between the PVC aggregates and cement paste due to the hydrophobic nature of plastic. On the other hand, a strong ITZ can be formed in the interface between the natural aggregates and cement paste. Weak bonding between aggregates and cement paste also forms micro-cracks under any kind of loading as can be seen in Figure 6b. As the plastic content increases, free water around the aggregates weaken the interface between the plastic and cement paste resulting in a less dense zone with large voids in the matrix [30]. This is a factor contributing to a decrease in the mechanical strength of PVC mixed concrete [11].

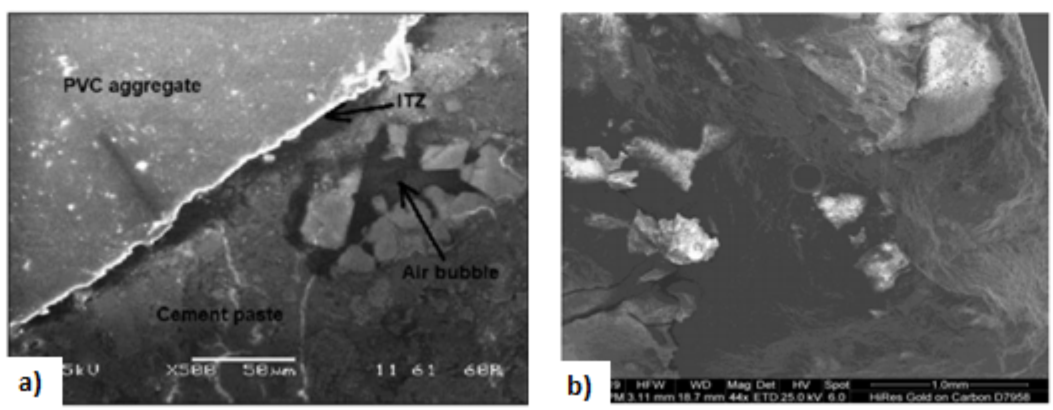

Figure 6:*SEM images of microstructure of concrete with (a) ITZ between PVC aggregate and cement paste and (b) cracks in PVC mixed concrete* [11, 17]

5. Concluding remarks

Over the last few decades, there has been much research work performed on the different properties of concrete with various percentages of plastic waste. This paper aimed to summarize the fresh, mechanical, durability, and microstructural properties of PVC mixed concrete from the available literature. From the above discussion, the following conclusions can be drawn:

- The resistant nature of PVC aggregates may supply better workability of concrete. However, the size and shape of the PVC aggregates play a key role in workability. The angular shape of PVC aggregates may increase the friction between the particles and thus reduce the workability.
- The mechanical properties of concrete reduce as the percentages of PVC aggregates increase. And 10% PVC replacement is acceptable for many applications.
- Water absorption and shrinkage of PVC mixed concrete are lower than the reference concrete. At a lower replacement level of PVC (5-10%), no noticeable difference can be found in UPV of concrete. Chloride ion penetration resistance is also better in PVC mixed concrete when compared with reference concrete.
- The hydrophobic nature of PVC aggregates forms weak ITZ in the interface between the aggregates and cement paste, which can lead to the lower mechanical strength of concrete.

For future studies, the mechanism of lower mechanical strength of PVC mixed concrete must be studied. Also, the long term performance of concrete with PVC aggregates should be investigated to grow the confidence of using this in concrete.

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