Durability of Recycled Aggregate Concrete with Conventional and Equivalent Mortar Volume Method: A Review

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Abstract - *Recycling construction wastes to prepare structural concrete is an effective measure to solve the dual problems of resource shortage and environmental pollution. RA is an alternative and reliable source for replacement of naturalaggregates. The concrete structures in service always subject tothe coupled effect of multiple environmental factors such as chloride attack, carbonation, water penetration and aggressive agent penetration etc., which accelerates the deterioration of durability. Durability resistance of recycled aggregate concrete with diverse substitution rates using conventional mix proportion compared with equivalent mortar volume method under different factors are reviewed in this paper. Durability resistance of RAC with conventional and equivalent mortar volume mix method results from several research are consolidated in this review paper*.

Key Words: **Chloride attack, Durability, RAC (Recycled Aggregate Concrete), RCA (Recycled Coarse Aggregate), Carbonation, EMV (Equivalent Mortar Volume).**

1. INTRODUCTION

In the new context of a circular economy where the environmental aspect is highlighted, the exploitation of natural resources and generation of waste must be reduced. The recycling of the old concretes can contribute to reduce the extraction of the natural resources and to reduce the waste deposit areas. For the resources conservation, cleaner production and sustainable development, RAC is considered as an ideal alternative to the traditional concrete. Therefore, exploring the feasibility of RAC used as structure concrete to expand the application range and improve utilization rate of C&DWs is significant. Durability is one of the main topic of concern while using recycled aggregates in concrete constructions. The concrete structures in service always subject to the coupled effect of multiple environmental factors such as chloride attack, sulphate attack, carbonation, and aggressive agent penetration etc., which accelerates the deterioration of durability. The properties related to the durability are usually the risks of steel reinforcement corrosion (carbonation, chloride penetration, air/water permeability, porosity).

2. RECYCLED AGGREGATE

British standard BS 8500-2 **(BSI, 2006)** defines RCA as recycled aggregate with maximum masonry/fines content of 5%, maximum lightweight material/asphalt content of 0.5% and maximum other foreign materials content of 1%. Recycling of demolished concrete into aggregate is environmentally beneficial by preserving natural resources, by waste reduction and by preserving landfill space. The properties of recycled aggregate mainly depends on the properties of its parent aggregate concrete and also on the quantity and quality of cement mortar, which is attached to the grains of recycled aggregate and on recycling methods.

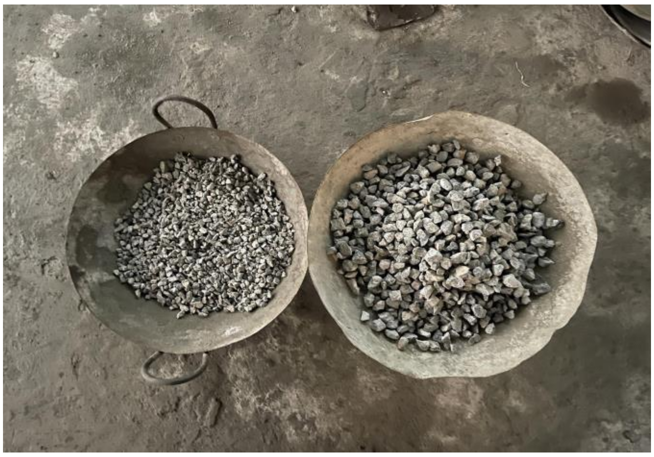

Fig -1: Recycled aggregate of size range 12.5mm and 20mm

From practical experience, **Mirjana** shown that the bulk density of recycled aggregate was on the average by 10% lower compared to the bulk density of natural aggregates [2]. The researchers from the University of Hong Kong recommend that the amount of recycled aggregate in structural concrete should range from 20% to 30%, in order to ensure that the maximum water absorption of aggregate used is less than 5%. [3]The water absorption value of the classically recycled coarse aggregate ranges within the interval from 3.5% to 10%, and for the fine aggregate, within the range of 5.5% to 13% from the results of **Marinković** [3].

3. PROPERTIES OF RECYCLED AGGREGATE CONCRETE

From studies of **Sherif Yehia,** concrete made with RA showed less durability due to high pore volume which led to high permeability and water absorption. High water absorption is due to cement paste adhered on the aggregate surface [9]. More water is needed for RAC to achieve similar workability to that of NAC due to higher absorption capacity of recycled aggregate, due to the presence of impurities and attached cement hydrates. As the RA content increases in the mix, the workability reduces especially at lower w/c ratio [10]. **Malesev** experiments showed that for 50 to 100% replacement of virgin aggregates with the recycled aggregate decreases the compressive strength by 5 to 25 % and a reduction of up to 10% in split tensile strength was observed when virgin aggregate was substituted with recycled aggregate, also flexural strength reduction was observed to be 10% that of RAC [11]. Specific gravity and bulk density are relatively low for recycled aggregates when compared to fresh granite aggregate. This is mainly due to the high water absorption of the RA, as mortar has higher porosity than aggregates and as the size of recycled aggregate increases, achieved strength increases [12].

4. MIX DESIGN METHODS

4.1 Conventional method

In studies made by **Emmanuel**, the conventional methods include the absolute volume approach according to the American Concrete Institute (ACI) standard or the Department of Environment (DoE) concrete mix design method given by the British specification [13]. A percentage of natural aggregates are replaced with recycled aggregates in this method without quantitatively considering the attached old mortar on the recycled aggregate. Conventional methods require more cement content compared to that proportioned using the EMV mix design method [13]. Here RCA is treated as a homogenous material as that of natural aggregate.

4.1 Equivalent mortar volume method

RCA is considered as a two-phase material comprising residual mortar and original virgin aggregate. In the proposed method, the RCA concrete mix is proportioned to have the same TM volume as a companion concrete mix made entirely with fresh NAs, with the companion mix made with the same type of coarse aggregate as that in RCA. The salient feature of the proposed mix design method is the treatment of RM in RCA as part of the TM content of RCA concrete.

Fig -2: Recycled aggregates containing attached mortar

Fig -3: Recycled aggregates devoid of attached mortar aftertreatment

Concrete proportioned based on this concept is shown to have the same or superior fresh and hardened properties compared to equivalent conventional concrete with the same amount of mortar [14]. Steps in determination of equivalent mortar volume mix method involves: Determination of companion concrete mix proportions made with natural aggregate. That is the determination of required RCA and fresh natural aggregate proportions in companion RCA concrete mix. Determination of required water, cement, and fine aggregate proportions and minimum replacement ratio in RCA concrete mix. Maximum residual mortar content in RCA concrete mix made with 100% RCA through an equation given by **G. Fathifazl** and through an experiment the residual mortar content of recycled aggregate can be measured.

5. DURABILITY FACTORS

5.1 Chloride attack

. All RCA-concrete examples made from mixtures proportioned using the EMV approach were found to have apparent chloride diffusion coefficients of the same order of magnitude as specimens made from traditional structural-grade concrete. In fact, RCA-concrete specimens without additional cementitious ingredients and proportioned using the EMV approach had apparent chloride diffusion coefficients that were lower than those of specimens prepared of mixture and proportioned using the traditional method. The resistance

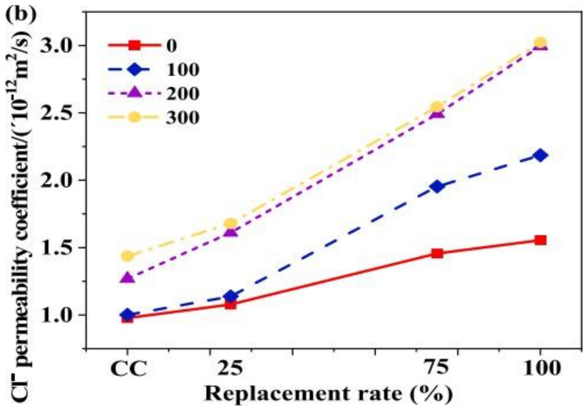

Fig -4: The variation trend of chloride diffusion coefficientwith substitution rate.

to chloride penetration of RCA-concrete specimens made of mixtures proportioned by the EMV method was improved by the addition of supplementary cementitious materials (fly ash or bfs) as partial replacement for ordinary portland cement. . In comparison to the reduction brought about by the inclusion of fly ash, the addition of bfs decreased the apparent diffusion coefficient of RCA-concrete mixes created using the EMV method by 120–200 percent. According to **Abdelgadir Abbas**' analysis, using the EMV approach in combination withadditional cementitious elements results in concrete that is highly resistant to chloride penetration. [6] Concrete's resistance to chloride corrosion was evaluated. At four separate F-T cycles, the total passed charge with regard to theRAC was calculated (0, 100, 200 and 300 cycles). It demonstrated a substantial link between the overall charge passing amount, the RCA substitution level, and the number ofF-T cycles. According to ASTM C1202 (2012), the ability of chloride to penetrate is low for total passed charges between 1000 and 2000, moderate for charges between 2000 and 4000, and high for charges beyond 4000 coulombs. As shownin Fig. 4, the results revealed that, with the exception of RAC- 25, all RAC had a high level of permeability after 300 F-T cycles. The ancient mortar's excessive porosity and microcracks on the RCA surface are the cause of the high chloride ion permeability. More chloride ions can enter the RAC specimens because there are more holes and microcracks that have created and connected flow channels. In addition to sulphoaluminate cement, fly ash and silica fume are mineral admixtures that can increase the durability of concrete. The quality of RCA and the type of concrete used are the main determinants of how long recycled concrete will last in a challenging environment. Therefore, concrete and RCA modification procedures might be taken into consideration in order to increase the RAC's durability and utilisation rate. [1] This condition is caused by the old mortar's high porosity and microcracks, which cause a high permeability for chloride ions. The F-T cycles make this damage worse. The resistivity of recycled aggregate concrete to chloride ion penetration was still lower than that of regular aggregate concrete after ten years of outdoor exposure. Fly ash greatly increased the concrete mixture's resistance to chloride ion penetration [16].

5.2 Freeze thaw cycles

According to the ASTM C 666-97 protocol, rapid freezing and thawing in water was used for the freeze-and-thaw experiments [15]. For a maximum of 300 cycles, the relative dynamic modulus of the test prisms was measured in order to track the freeze-and-thaw damage. By taking an accurate transverse frequency reading of the specimens, one can calculate the relative dynamic modulus. The durability factor served as a representation of how well concrete performed in freeze-and-thaw conditions. A strong resistance to freeze- and-thaw action can be observed in RCA-concrete mixes proportioned by the traditional mix design method (100 percent RCA content) or by the EMV method (63.5 percent and 74.3 percent RCA content for RCA-concrete made with RCA- MO and RCA-VA, respectively).

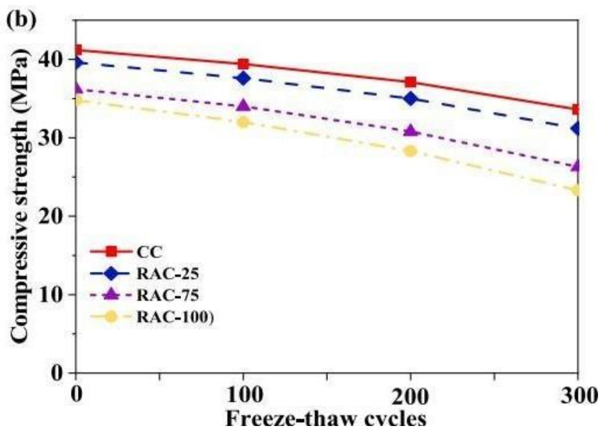

Fig -5: Compressive strength of recycled conventional concrete (conventional mix method)

However, the EMV approach provides concrete with greater resilience to freeze-and-thaw action than RCA-concrete proportioned by conventional mix design method [6] becauselower total mortar content in RCA-concrete can be attained using this method. More chloride ions can enter the RAC specimens thanks to a rise in F-T cycles, more holes and microcracks, and the formation of interconnected flow pathways.

5.3 Carbonation

A setup based on advice from RILEM was used to conduct a carbonation test. The carbonation depths of RCA-concrete, both with and without additional cementitious ingredients, are within the range anticipated for ordinary structural-grade concrete. The least amount of carbonation was found in RCA- concrete specimens without additional cementitious ingredients, followed by examples with fly ash. The reserve alkalinity of the concrete's binder is the primary factor impacting the carbonation of RCA-concrete, according to specimens created with concrete proportioned using the EMV method. It was discovered that specimens with a high cement content had a high resistance to carbonation. The carbonation coefficient for mixes created using the EMV approach, however, was lower or equivalent to that of mixes created using the conventional method for specimens containing fly ash [6]. Concrete's carbonation coefficient improved as recycled aggregate and fly ash contents increased [16]. If all other parameters are equal, larger carbonation depths result from the assimilation of increasing amounts of RA. Concrete made entirely of coarse RCA has the potential to carbonate at up to twice the rate of similar NAC mixes. Regarding the RA type effect on carbonation, it was discovered that RMA create deeper carbonation depths than RCA for a given replacement level. In an MRA blend, the depth of carbonation in the final concrete increases as the RMA con- tent increases. Since concrete porosity and carbonation are intimately related, it follows that adding more porous RA will make concrete more permeable and so allow for deeper carbonation. An efficient way to improve mechanical performance and decrease carbonation in RAC mixes is to lower the w/c ratio with the use of water lowering admixtures. It was also determined that controlling the quality and quantity of RA in the mix is preferred because these factors have a stronger impact on this characteristic than reducing the w/c ratio by adding water- reducing admixtures.

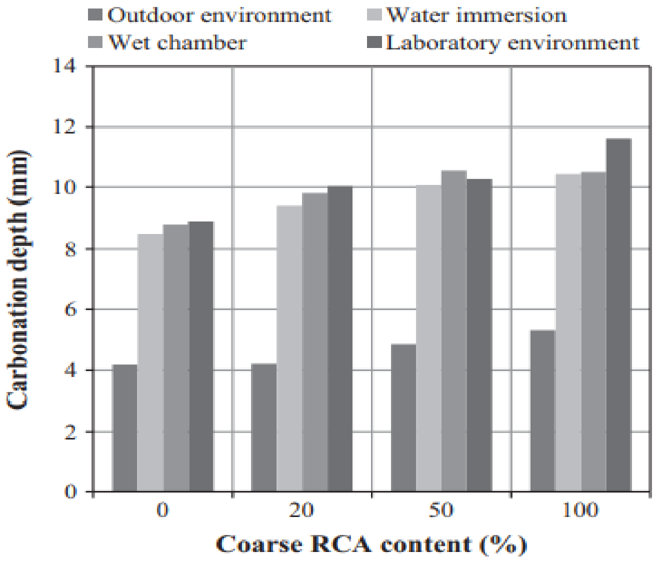

Fig -6: Carbonated depth of concrete cured in different environments (adapted from Amorim et al.)

The use of mineral additions as cement replacement causes greater carbonation depths than those of mixes without them. This happens because the $Ca(OH)_2$ content decreases thus lowering the pH of concrete. Nevertheless, irrespective of the presence of RCA, the difference in carbonation depth is similar over time to that of the corresponding NAC, with or without any mineral additions [17].

5.4 Water penetration

Test was performed by introducing the specimens into a device in which they were submitted to a water pressure equal to 500 kPa for a period of 72 hr, after that specimen is cut in half in order to determine the water penetration depth. Each mix class result of the water permeability test was obtained from the average of three different specimens. The results for every ACI mix, compared to their correspondent EMV ones, show higher water penetration. There also seems to be an improvement when comparing the specimens by type of RCA. In the majority of the cases, the use of the novel method improves the concrete behavior on this specific property when comparing it to the conventional RAC and, when using small replacement amounts of RCA, the EMV method achieves similar values to those of a conventional concrete. These behaviors can be explained by the concrete mixes characteristics as it has been mentioned before, which are certainly closer to those of a NAC than to a conventionally designed RAC [15]. ACI based mixes proportioned by the EMV method, in both 0.45 and 0.6 w/c ratios, show better behavior in the capillary absorption and water penetration properties than the RAC prepared with conventional methods.

6. CONCLUSIONS

EMV method proved to be the most efficient method of mix proportioning rather than the conventional replacement of aggregate method. Reducing the total mortar content in concrete was the main reason to achieve better results in strength and durability. Also the physical features of recycled aggregate like rough texture and angular nature contributes to strength characteristics of recycled concrete. Adjustments in mix proportioning helped to achieve more durable mix. Studies relating to durability issues regarding recycled aggregate concrete are still going on worldwide.

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