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Investigating the Effect of Error in Determining Residual Mortar in EMV Method of Proportioning Recycled Aggregate Concrete

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Abstract- Concrete from construction and demolition (C&D) waste may be reused as coarse recycled concrete aggregate (RCA) thus reducing the usage of natural aggregates and conserving their sources. RCA is a two-phase material that consist of original virgin aggregate and adhered mortar which is the residual mortar content (RMC). Equivalent mortar volume (EMV) method of proportioning of recycled aggregate concrete consider RCA as a two-phase material and deduct residual mortar volume from the total mortar volume to get the fresh new mortar volume whereas in conventional aggregate replacement method, RCA is considered as a single phase material. The project aims to determine the residual mortar content of the RCA and to evaluate the effect of errors incorporated with RMC in the fresh and hardened properties of RCA concrete made by EMV method. A large number of mixes are to be made with RCA using EMV method and for each mix, its slump, compressive strength, flexural strength, split tensile strength and elastic moduli are measured. The fresh and hardened properties of RCA concrete made by conventional percentage replacement method has to be evaluated to compare it with the RCA concrete made by equivalent mortar volume method.

Keywords- Conventional Percentage Replacement Method, Equivalent Mortar Volume, Mechanical Properties, Natural Coarse Aggregate, Recycled Aggregate Concrete, Residual Mortar.

I. INTRODUCTION

Construction industry plays a crucial role in the development of a nation by contributing significantly to the economic growth and gross domestic products (GDP) of many countries. Construction process involves planning, financing, designing and development of the project for the client utilization which is followed by repair and maintenance work and eventually extends to the demolition and dismantling of the structure at the end of service life or when destroyed by natural disasters and wars. Demolition phase which is the last stage of construction process produce tonnes of Construction and Demolition waste commonly known as C&D waste. Annually around 3 billion tonnes of C&D waste is being generated in the global scale. Disposal of C&D waste is often a nuisance to environment as it cause pollution and health hazards. C&D waste is generally used for landfilling which results in reducing the fertility of land. Concrete which is the major construction material and the main C&D waste can be reused as recycled concrete materials. Concrete from C&D waste is processed to make recycled concrete aggregates which can be used as a replacement to the natural aggregates. Usage of Recycled concrete aggregates as fine or coarse aggregate can reduce the mining of natural aggregates and preserve natural sources.

II. RECYCLED CONCRETE AGGREGATE

Concrete is segregated from C&D waste and is processed to the get the **Fathifazl et al. 2009**required size as in the form of either coarse aggregates of size ranging from 4.75 mm to 40 mm or fine aggregates of size ranging from 150 micron to 4.75 mm (**IS 383, 1970**). Commonly recycled coarse aggregates are used for experimental studies. During the crushing process of concrete, adhered mortar with low strength will be removed from required particles. Only the mortar having higher strength or higher bond strength will adhered to the surface the aggregate thus resulting in a two-phase material. Recycled concrete aggregate (RCA) is a two-phase material that consist of natural virgin aggregate and adhered mortar. This adhered mortar is known as Residual mortar. The quality and the physical properties of RCA affect the quality and properties of the concrete produced by using RCA as coarse aggregate. The amount and the quality of adhered mortar influence the physical properties of RCA **(Etxeberria, Vazquez, Mari, Barra,**

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2007). RCA has higher water absorption which is due to the presence of porous adhered mortar **(Guoliang, Zhu, Liu, Biao, 2020)**. Adhered mortar is also responsible for the lower density of RCA **(Jeonghyun, 2021).** Higher water absorbing property of RCA results in the lower workability of concrete made using RCA which is known as Recycled aggregate concrete (RAC) **(Guoliang, Zhu, Liu, Biao, 2020)**. This lower workability of RAC can be compensated by presoaking the RCA. Several researches showed that RCA has inferior physical properties when compared to Natural aggregates.

Natural coarse aggregate

Recycled coarse aggregate containing attached mortar

Figure 1

III. RECYCLED AGGREGATE CONCRETE: MIX PROPORTIONING

1. CONVENTIONAL PERCENTAGE REPLACEMENT METHOD

Recycled aggregate concrete (RAC) is obtained by the partial or full replacement of natural coarse aggregate (NCA) with RCA in concrete. There is no exact specification for the mix proportioning of RAC. A conventional method of RAC mix proportioning is the percentage replacement method in which several percentage of NCA is replaced with RCA. **Jianzhuang Xiaoa, Jiabin Lia, Ch. Zhangb, (2005)** conducted study on the recycled aggregate concrete by testing different RAC specimens with RCA replacement percentages as 0%, 30%, 50%, 70% and 100%. Size of the aggregates ranges from 5-31.5mm. Water absorption of RCA was found to be 9.25% which is higher than that of NCA (0.4%). So presoaking of RCA was adopted. RCA also possess lower density and higher crushing index when compared to NCA Concrete with 0% RCA is the normal concrete with NCA. As the RCA content increases, the slump was found to be reduced because the higher absorption capacity of RCA makes the concrete stiffer.

Another study conducted by **Sumaiya B. Huda1, M. Shahria Alam, (2015)** evaluated the mechanical and freeze-thaw durability of four mixes with RCA replacement percentages as 0%, 30%, 40% and 50%. RCA also contain impurities along with the adhered mortar which can influence the properties of RAC. Specific gravity of RCA is 2% lower than NCA with the value of 2.55. Water absorption of NCA was around 0.3% and higher water absorption for fine and coarse RCA was observed to be in the range of 3.2-12%. RCA had lower abrasion resistance with a value 12% lower than that of NCA. Since RCA was used in unsaturated condition, a portion of mixing water was found to be absorbed by the recycled aggregate and reduced the amount of water in the mix. So adjustments were made in the total amount of water considering the moisture condition and the water absorption of both the aggregates. RCA with maximum size of 14mm was used. The study commented that RCA having size over 19mm, can reduce the strength of concrete due to the presence of increased interfacial zone. RCA had a specific gravity 2.55 which was lower by 5% than that of natural coarse aggregate. It is due to the adhered mortar of RCA. A gradual reduction in the slump was observed from 100mm to 90mm when the percentage replacement increases from 0-50%.

M. Etxeberria, E.Va´zquez, A. Marı (2006) conducted microstructural analysis on hardened recycled aggregate concrete having four replacement percentages of 0%, 25%, 50% and 100%. Natural aggregates present in the recycled aggregate had inferior quality when compared to the conventional natural coarse aggregates. There are two interfaces existing in RCA, the interface between attached mortar and the original natural aggregate, and the new interfacial transition zone between the new binding mortar and the RCA. Unsaturated but wet RCA was used in the mixing which will aid the cement to adhere to the aggregate surface and fill the pores.

2. EQUIVALENT MORTAR VOLUME METHOD

Conventional percentage replacement method consider RCA as an original aggregate whereas in equivalent mortar volume (EMV) method of mix proportioning RCA is treated as a two-phase material consisting of original natural aggregate and attached mortar known as residual mortar **(Fathifazl et al. 2009).** In conventional percentage replacement method Total Mortar (TM) volume consists of residual mortar (RM) and the fresh mortar. So when compared to the control mix made with 0% RCA, RAC has larger TM volume. Higher TM volume can result in the inferior mechanical and physical properties of RAC than the normal concrete with NCA. EMV method of mix proportioning maintain the same TM volume as in control mix by finding the residual mortar content in RCA and deducting the RM value from the fresh mortar. **Fathifazl et al. (2009)** proposed a mix design for EMV mixes. He used air entraining agents and mineral admixtures like fly ash and blast furnace slag to increase the content of binding mortar when the RMC value obtained was greater and there was no enough fresh mortar for binding. So determining RMC

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value is crucial in EMV method of mix proportioning.

Determination of RM content

The primary step in EMV method is the determination RM content. Several representative samples of RCA is subjected to several freeze-thaw cycles while being immersed in sodium sulfate solution (**Abbas et al. 2008).** Each representative sample contain 1000 g of RCA of size ranging from 4.75- 12.5 mm and 2000 g of RCA of larger fraction. Samples are oven-dried for 24 hours at 105ºC and then immersed in 26% by weight sodium sulfate solution for 24 hours. RCA samples while immersed in sodium sulfate solution is subjected to five cycles of freeze and thaw cycles. Freezing of samples are done at -17ºC for 16 hours and then thawed at 80ºC for 8 hours. After the last freeze and thaw cycle, sodium sulfate solution is drained out of the samples and washed with water over a 4.75 mm sieve. Then the aggregate samples are oven dried at 105ºC for 24 hours and the weight of the remaining samples are taken. The RMC vale can be obtained using

$$RMC\% = \left(\frac{Wrca - Wova}{Wrca}\right) \times 100 \quad (1)$$

Wrca= initial mass of oven dried RCA sample before testing in grams

Wova= final mass of oven dried OVA after RM removal in grams.

Proposed Mix Design

First a companion concrete is designed using conventional mix design method using natural aggregate as coarse aggregate and let this concrete be termed as natural aggregate concrete- NAC. Let V_{NA}^{NAC} represent the volume of NCA in NAC and V_{NA}^{RAC} be the volume of NCA in RAC. For RAC to have the same properties of NAC, two conditions should be satisfied

i.e. $V_{TM}^{RAC} = V_M^{NAC}$ (2)

and $V_{TNA}^{RCA} = V_{NA}^{NAC}$ (3)

V_{TM}^{RAC} – volume of TM in RAC

V_M^{NAC} – volume of mortar in NAC

V_{TNA}^{RCA} – volume of total NCA in RAC which is the sum of fresh NCA and original virgin NCA in RCA which is represented as OVA.

$V_{TM}^{RAC} = V_{RM}^{RAC} + V_{NM}^{RAC}$ (4)

$V_{TNA}^{RCA} = V_{OVA}^{RAC} + V_{NA}^{RAC}$ (5)

V_{RM}^{RAC} – volume of RM in RAC

V_{NM}^{RAC} – volume of new mortar in RAC

V_{OVA}^{RAC} – volume OVA in RAC

V_{OVA}^{RAC} can be determined by knowing the specific gravities of OVA in RAC and RCA.

$$V_{OVA}^{RAC} = V_{RCA}^{RAC} \times (1 - RMC) \times \frac{Srca}{Sova} \quad (6)$$

V_{RCA}^{RAC} – RCA volume in RAC

Srca – specific gravity of RCA

Sova - specific gravity of ova

Using the above equations, the required weghts and volumes of fresh NCA and RCA for RAC can be found as follows:

$$V_{RCA}^{RAC} = [V_{NA}^{NAC} \times (1-R)] / [(1-RMC) \times \frac{Srca}{Sova}] \quad (7)$$

$$R = V_{NA}^{RAC} / V_{NA}^{NAC} \quad (8)$$

$$W_{OD\ RCA}^{RAC} = V_{RCA}^{RAC} \times Srca \times 1000 \quad (9)$$

$$W_{OD\ NCA}^{RAC} = V_{RCA}^{RAC} \times Snca \times 1000 \quad (10)$$

$W_{OD\ RCA}^{RAC}$ = oven-dry weight of RCA in RAC

$W_{OD\ NCA}^{RAC}$ = oven-dry weight of fresh NCA in RAC

and Snca = specific gravity of NCA.

Volume RM in RAC can found using

$$V_{RM}^{RAC} = V_{RCA}^{RAC} \times [1 - (1-RMC) \times \frac{Srca}{Sova}] \quad (11)$$

Volume of fresh RAC can be found as

$$V_{NM}^{RAC} = V_M^{NAC} - V_{RM}^{RAC} \quad (12)$$

Thus weight of cement, fine aggregate and water in RAC can be determined as:

Weight of cement in RAC,

$$W_C^{RAC} = W_C^{NAC} \times (V_{NM}^{RAC} / V_M^{NAC}) \quad (13)$$

Weight of fine aggregate in RAC,

$$W_{FA}^{RAC} = W_{FA}^{NAC} \times (V_{NM}^{RAC} / V_M^{NAC}) \quad (14)$$

Weight of water in RAC,

$$W_W^{RAC} = W_W^{NAC} \times (V_{NM}^{RAC} / V_M^{NAC}) \quad (15)$$

The maximum permissible RM content for RAC mixes with 100 % RCA can be determined as

$$RMC_{max}\ \% = [(1 - V_{DR\text{-}NA}^{NAC}) \times \frac{Snca}{Srca} \times 100 \quad (16)$$

If the RMC value greater than $RMC_{max,}$ then it is not possible to completely replace NCA by RCA.

IV. MECHANICAL PROPERTIES OF RECYCLED AGGREGATE CONCRETE

1. CONVENTIONAL PERCENTAGE REPLACEMENT METHOD

Compressive strength

RAC designed by percentage replacement method often shows inferior mechanical and physical properties when compared to NAC. The reason for this inferior quality is the presence of higher amount of total mortar which comprise of both old attached mortar and the fresh mortar. In RAC the amount of natural coarse aggregate is lower than that in NAC. Study conducted by **Jianzhuang Xiaoa, Jiabin Lia, Ch. Zhangb, (2005)** showed that the compressive strength of RAC is greatly influenced by the RCA contents. The results obtained by conducting compression test shows a decreasing pattern of compressive strength with increasing RCA content. **Sumaiya B. Huda1, M. Shahria Alam, (2015)** conducted cylinder compression tests after curing for 3, 7, 28, 56, and 120 days. Results obtained was similar to the previous study that is as the RCA replacement percentage increases the compressive strength decreases. The study also pointed out some major causes behind the

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strength degradation of RAC. Weaker Interfacial transition zone between concrete clusters caused by the high amount of adhered mortar on the surface of RCA and inadequate hydration are the major causes. Low bulk density and attached mortar of RCA influence the strength of RAC.

Split Tensile strength

According to the study conducted by **M. Etxeberria, E.Va´zquez, A. Marı (2006)** split tensile strength of RAC decreased by 6%, 10% and 40% of that of NAC when RA replacement ratio were 25%, 50% and 100%. Split tensile strength was influenced by the quality of aggregate. Quality of RCA is lower due to the presence of porous attached mortar. Decrease in tensile strength of RAC is caused by the mixes containing larger coarse aggregates with lower mortar strength caused by the higher effective water- cement ratio.

Flexural strength

Guoliang Bai, Chao Zhu, Chao Liu, Biao Liu. (2020) reported that the flexural strength was 6%, 13% and 26% lower for RAC with 25%, 50% and 100% replacement when compared to NAC. This behavior is due to the poor bonding quality between the old attached mortar and the fresh mortar. Use saturated RCA can also attribute to the lower flexural strength. Since water absorption of RCA is higher, water-binder ratio is increased which can also contribute to the lower flexural strength.

Modulus of Elasticity

Modulus of elasticity of concrete depends on the elastic moduli of both aggregate and mortar. Results obtained from the study conducted by **Togay Ozbakkaloglu, Aliakbar Gholampour and Tianyu Xie. (2018)** showed that lower the RCA percentage higher is the modulus of elasticity. Elastic modulus of concrete can be correlated with the volume fraction, quality of aggregates and its compressive strength. As the percentage of replacement of RCA increases the concrete become more stiff with less strength thus reducing the modules of elasticity.

2. EQUIVALENT MORTAR VOLUME METHOD

Compressive strength

Using the EMV method **Fathifazl et al. (2009)** obtained 6% - 13% higher compressive strength for all the EMV mixes compared to the NAC. The higher compressive strength was obtained for mix with higher RMC 41% and blast furnace slag was added as filler material to densify the microstructure of hydrated cement paste which resulted in the increase in strength. **Jeonghyun Kim. (2021)** compared the conventional percentage replacement and EMV mixes and obtained that for 25%, 50%, and 100% of RCA replacement, the compressive strength of RAC made with high-quality RA was found to be 30.9 MPa, 29.3 MPa, and 28.1 MPa, and the RAC with low-quality RA was 27.9 MPa, 25.8 MPa, and 23.6 MPa. But for EMV mixes, the compressive strength was in the range of 29.3 – 31.5 MPa irrespective of the RA quality and replacement ratio. Thus, the authors concluded that the total mortar volume has significant influence on the compressive strength of RAC.

Split Tensile strength

Emmanuel et al. (2020) reported that EMV mix show higher value for split tensile strength than NAC. The authors also showed that the split tensile strength of RAC depends mainly on the quality of RCA. The test results showed 12% increase in the split tensile strength of EMV mix with RMC 40% when compared to conventional NAC. **Jeonghyun Kim. (2021)** conducted test and obtained tensile strength of the EMV concrete with 30% of RMC as 8% higher than that of NAC. Authors concluded that because of its rougher surface RCA adheres better to the cement paste than NCA, which resulted in the increased value of tensile strength of RAC.

Flexural strength

Jeonghyun Kim. (2021) reported that the flexural performance test results showed that the ultimate moments of the RC beams designed by EMV method with 40% RMC, has value 1% higher than that of the conventional RAC beam with 40% of RCA replacement.

Modulus of Elasticity

Test results from the study conducted by **Fathifazl et al. (2009)** reported that the modulus of elasticity of EMV concrete was 0–5% and 5–11% higher than that of NAC and RAC made by percentage replacement method. Increased total mortar volume could be a critical factor that caused the decrease in the elastic modulus of conventional RAC. The study also suggest that the quality of RCA can influence the elastic modulus RAC. Inferior quality RCA can result in lower elastic modulus even for EMV mixes. RCA have lower modulus than NCA which can affect elastic modulus of RAC with increasing replacement ratio. Modulus of Elasticity can decreases even when the strength increases. But this trend was not observed in the EMV mix design method.

V. CONCLUSION

This paper reviewed the physical and mechanical properties of recycled aggregate concrete made two mix proportions, conventional percentage replacement and equivalent mortar volume methods of mix proportioning. RCA consist of natural aggregate and attached mortar. This attached mortar is responsible for the inferior properties of RCA like porosity, higher water absorption and lower specific gravity. These inferior qualities of RCA can influence the several physical and mechanical properties of RAC. Properties of RAC is greatly influenced by the method of mix proportioning. Conventional percentage replacement method provide RAC with low Compressive

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strength, Modulus of elasticity, split tensile strength and flexural strength with increasing replacement ratios when compared with that of natural aggregate concrete. EMV method of mix proportioning appears to make a better result than the conventional replacement method. Higher values of mechanical properties are obtained from EMV mixes. EMV mixes are designed according to the residual mortar content present in the RCA. In EMV mix RMC is deducted from the total mortar content, thus reducing the amount of fresh mortar needed for binding. This method has environmental benefits like reducing carbon emission during hydration, reducing the use of natural aggregate. Usage of recycled concrete aggregate can reduce mining for aggregate and thus natural aggregate sources can be conserved.

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The recent studies of EMV method of mix proportioning deduct the residual mortar volume from the total mortar volume in order to obtain the volume of fresh mortar required enough for binding. Residual mortar content is obtained from different representative RCA samples and taking the average to get the RMC value required for EMV method of mix proportioning. There are no relevant studies evaluating the effect of error in determining the RMC on the different mechanical properties of concrete mixes designed using EMV method. Comparative study of mechanical properties of different mixes designed by conventional percentage replacement method and different mixes proportioned by EMV method considering errors in RMC value can be done as a new study in this area.

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