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A Review on Recycled Asphalt Pavement in cement concrete

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Abstract: Utilization of industrial and infrastructural wastes in civil engineering applications has been gaining a major importance. Most of the recent studies are focused on innovative solutions with respect to sustainability, due to growing needs of urban societies. It was found that the research studies on utilization of RAP (which is an infrastructural waste) in different civil engineering applications is becoming more popular day by day. This paper discussess review over the properties of RAP aggregates in comparision to the natural aggregates, which includes physical, mechanical and chemical. Apart from the aggregate properties, this paper also presents the fresh and hardened properties of RAP inclusive concrete. It was observed that due to the increment in RAP, when replaced for natural aggregates, the strength decreases following a standard trend. It was found that due to the presence of asphalt film over the RAP aggregates, the modulus of elasticity of RAP inclusive concrete was less in comparison with concrete made of natural aggregates. Due to this the RAP inclusive concrete can sustain higher strain values than the concrete made of natural aggregate, which will be helpful in the case of cyclic loadings and impact loadings.

Keywords: Asphalt, Concrete, Elastic modulus, RAP, Strain, Strength.

I. Introduction

Urbanization is growing in the present days, where people are looking for a comfortable life with safe shelter and well-connected roads for transportation. To meet these basic needs people are heavily dependent on the natural resources. This results in depletion of natural resources. Especially in construction industry; water, aggregates and cement are one of the major ingredients. To address the above issue we have to practice industrial ecology, i.e. treat the waste of a particular industry as a raw material for other industry. In case of aggregates, the present study looks at alternative resources which can replace the available natural resources. Most of these alternative resources are recycled aggregates e.g., Recycled Concrete Aggregates (RCA), mining wastes like Iron Ore Tailings and infrastructural wastes such as RAP (Recycled Asphalt Pavements). This article focuses on recent findings on studies for RAP as alternative resources.

Table 1 indicates the data as per the Hassan [1] and Hossiney [2], where it was also mentioned that up to 10 % to 40% of the demolition wastes in the UK are recycled and used in low grade applications. Due to the lack of standards on the recycled aggregates, high grade applications were restricted.

In the field of construction, steel is being used as reinforcement in the concrete to provide ductility to the concrete members, this led to the increase in the production of steel. India is standing in the fourth place in the production of steel. As per a survey, in Malaysia about 625000 tons of IOT is being produced every year which is termed as a serious environmental issue. Recently the government of Karnataka in India has planned to ban IOT due to its bad impact on the environment. As a result of steel production, Iron Ore tailing is being produced as a waste product. It has become a challenge in disposing these tailings, due to increase in the production of steel. It is disposed as a waste in landfills, quarries, rivers and oceans. Due to these challenges and increase in the waste production, research works are being conducted to use tailings as a replacement of fine aggregates in the concrete and also masonry bricks were being made with various compositions of tailings [3]. Recycled Concrete Aggregates (RCA) is the product of demolition concrete structures such as buildings, roads and runways. The RCA is used as recycled aggregates in concrete and as landfills.

This paper is much interested in the review of applications and advantages of RAP as recycled aggregates in concrete and several pavement applications. Usually the reclaimed asphalt pavement materials which were generated are used at the same site as a land fill, embankment fill materials and as a sub-base which is economical and helps in saving time. According to Solanki [4], about 80% of the RAP which is reclaimed during road resurfacing and widening projects is recycled and used in pavement applications, but it was mentioned that several research works are being carried out on RAP as aggregated in concrete applications. The idea of replacing the virgin aggregates in concrete with the recycled aggregates is gaining much importance due to the demand and increase in the amount of wastage production every year. It was assumed that the presence of

the bitumen coating around the recycled aggregates may improve the toughness properties of the concrete incorporating RAP as aggregates [5] [6] [7].

This paper provides as clear vision on the properties of RAP aggregate in comparison with natural aggregates. Properties such as physical, mechanical and chemical properties were discussed in detail in consideration with concrete applications. Mainly those properties include specific gravity, absorption, sieve analysis, bulk density, Impact value, aggregate crushing value and abrasion resistance value. Apart from aggregate properties, the fresh and hardened properties of RAP inclusive concrete have also been discussed in this paper. The slump cone study was given much priority in the fresh properties of the concrete. The hardened properties like compressive strength, flexural strength, split tensile strength, toughness, permeability and acid resistance were discussed in detail.

II. Recycled Asphalt Pavement

Reclaimed asphalt pavement (RAP) is defined as the reclaimed and reprocessed pavement materials containing asphalt and aggregates and is produced by milling during reconstruction, resurfacing operations or to obtain access to buried utilities, or full depth removal of existing pavement layers which after proper crushing and screening consists of high-quality, well-graded aggregates coated by aged asphalt cement.

II.1. Physical and Mechanical Properties

Some of the physical and mechanical properties of aggregates usually include Specific gravity, Water absorption, Bulk density,Abrasion Resistance, crushing strength and Impact resistance etc., these are the major properties which helps in assessing the quality of the aggregates which are being used in the concrete mix. Hence, same tests have been carried out on the RAP aggregates by many researchers with an intension to determine the effective use of RAP aggregates in concrete applications. The following data provides the test results on properties of the RAP aggregates which were provided by various researchers.

The data provided in Table 2 was taken as an average by considering various available research data provided by different researchers. This data helps us to assess the quality of the RAP aggregates in comparison with the available natural aggregates.

Usually the specific gravity of the natural aggregates varies between 2.6 to 2.8. This property helps us in determining the quantity of the aggregates required for a particular mix of concrete. So by observations, The RAP aggregates have a lower specific gravity values as compared to virgin aggregates [8] [9].

The unit weight of RAP depends on the type of aggregate present in the pavement and the moisture content of the material. From previous literature on RAP, it was found that the unit weight of RAP ranges from 1940 to 2300 kg/m^3.[2] [10] [1] [8] The moisture content of RAP increases while it is still in storage since the RAP is exposed to rain. The stored RAP has been found to have a moisture content of up to 5 percent or higher [11]. The moisture content of RAP can go up to 7 to 8 percent during periods of heavy rainfall [12].

The mechanical properties like the crushing, impact and abrasion resistance are almost within the limits when compared with the natural aggregates especially when they are used for concrete pavement applications. RAP mainly depends on the original asphalt pavement type, properties of the materials present in RAP, the asphaltconcrete mix and the type of equipment used to produce the RAP. On surface course or wearing course asphalt concrete, the aggregates must have a high resistance to wearing/abrasion than the aggregates in binder course, where abrasion resistance is not important. Based on several research studies the LA abrasion resistance value for coarse RAP was found to be less than 38 percent, this implies that RAP aggregates does not have a uniform hardness [9] . So this data supports us to carry out the research study on RAP inclusive concrete applications. [13] [14]

The following are some of the findings drawn from variousresearch studies regarding the gradation of the RAP aggregates which were processed as coarse and fine in comparison with natural coarse and fine aggregates.

It was stated that there was an increment in the percentage of finer particles in RAP as aggregate degradation occurs due to milling or crushing [15]. The particle size distribution of RAP varies to some extent when compared to natural aggregates. The gradation of RAP was generally finer and denser than that of the natural aggregates. Fig.1 shows the gradation curves of RAP aggregates and natural aggregates together. It was observed that the coarse RAP was finer than the natural coarse aggregates and fine RAP was coarser than the natural fine aggregates which was due to the conglomeration of finer particles in the fine RAP. It can also be seen that the fine RAP was well graded in comparison with fine aggregate. This behavior was due to the presence of a huge amount of dust particles in fine RAP which fills the gap of gradation. [16] [17]

RAP contains a higher coarse aggregate angularity as compared to virgin aggregates [9]. This helps to improve the friction resistance of the aggregates of RAP. The optimum moisture content and maximum dry density of RAP increases when binder content in RAP is high and with a low fine aggregate angularity.[18]

The asphalt cement content of RAP ranges between 3 and 7 percent by weight. Due to environmental exposure, oxidation and weathering process occurs which causes the asphalt cement covering the RAP aggregates to become a lot harder. The hardened asphalt cement depends on multiple factors like the intrinsic properties of the asphalt cement, the mixing temperature/time which increases with increase in high temperature exposure, the degree of asphalt concrete compaction which when not compacted properly will increase, cement/air voids content which increases when there is a lower asphalt and higher air voids content, and service age (increases with age).

II.2. Chemical Properties

RAP contains mineral aggregates of 93% to 97% by weight and 3% to 7% of hardened asphalt cement. In comparison to the chemical composition of natural aggregates, RAP has a similar composition. From the XRF test results shown in Table-3, it was observed that the major element compounds of RAP are SiO_2, Fe_2O_3, CaO by percentage weight as similar to that of natural coarse aggregates [19].

The Asphalt cement around the aggregates is a combination of high molecular weight aliphatic hydrocarbon compounds along with low concentrated Sulphur, nitrogen and polycyclic hydrocarbons (aromatic and/or naphthenic) which are low reactive in nature and also a combination of asphaltenes and maltenes (resins and oils). The asphalt in RAP is a viscoelastic material, whose properties relies on temperature and also the loading conditions. The viscosity of the asphalt is determined by the asphaltenes rather than either resins or oils since asphaltenes are more viscous. As the RAP is exposed to the environment, oxidation causes the oils to convert to resins and the resins to convert to asphaltenes in the aged asphalt which results in age hardening and a higher viscosity binder [20] Due to oxidation (aging) of the binders, the carbonyl and sulfoxide indices within the RAP was increased [21]. The viscosity increases with an increase in the RAP binder content. So, it was assumed that this property of asphalt helps in reducing alkali silica reactions in aggregates. When RAP is used in concrete as a replacement for natural aggregates the workability decreases due to asphalt film present around the aggregates. Lowering the viscosity of the bitumen in RAP will help to get the required workability of the mixes. With the addition of RAP, the properties of concrete such as creep and shrinkage gets affected. During the summer months there is an increase in the temperature, this makes the asphalt to become softer which in turn affects the creep of the asphalt. [22]

III. Fresh Properties of Rap Inclusive Concrete

Usually the fresh properties of the concrete are controlled by various factors like cement content, water cement ratio, aggregate content, shape of aggregate and surface texture of the concrete etc., Workability is one of the fresh properties of concrete which is of major concern. As mentioned above workability of a concrete majorly depends on the water, quantity of cement and aggregate.

It is of great interest to study the behavior of RAP content in concrete mix when replaced in proportions with natural aggregates. Many research studies have been carried out on the workability of concrete mix when RAP was replaced with natural aggregates. One of the parameters which explains about workability is the slump cone study. Since RAP inclusive concrete is a new innovative concept most of the studies were confined to slump cone study case of fresh concrete.

It was found that the slump value of the fresh concrete mix was increased when RAP was replaced in smaller quantities. But, slump value drastically decreased when the RAP content was increasing. To know the more effective way, studies have been done on coarse and fine RAP separately. The results obtained by this study gave a clear version on the behavior of RAP replacement in concrete mix with different proportions. It was determined that slump value of the fresh concrete was very low when fully replacement of fine RAP was done when compared to the case fully replacement of coarse RAP which is shown in the fig. provided by "B. Huang et. al." in one of his research findings on RAP. [5] [6]

It was found the same, even with the findings of "Fidelis O. OKAFOR" on the RAP utilization in concrete mix. The followings are the results drawn from his research findings. It was stated that the low workability behavior of RAP aggregates was due to the asphalt mortar coating on the aggregate and also due to the rough irregular shape of the RAP aggregate. It was proved that the reduction in the workability of RAP inclusive concrete was about 50% when compared with the concrete containing natural aggregates. [23]

Apart from direct replacement of RAP aggregates in concrete, studies had also been done between processed and unprocessed RAP aggregates. Once of such studies was done by "Surender Singh et. al." on the processed and unprocessed RAP aggregates. The RAP aggregates were processed using the AT & BT method. It

was found that the initial slump value of the processed RAP is high when compared with the unprocessed RAP aggregates. When 25% of natural aggregates were replaced with processed RAP aggregates, the initial slump value was increased to 9.68% when compared with the unprocessed RAP aggregates. Similarly, the slump values were increased to 22.58%, 41.94% and 54.54% with 50%, 75% and 100% replacement of processed RAP respectively in comparison with unprocessed RAP. It was assessed that this behavior was due to the dirt particles in unprocessed RAP which has more water absorption compared to processed RAP. It was also noticed that the concrete with natural aggregates reached the zero-slump value in 45 min while the concrete with unprocessed RAP reached zero slump in 30 min, 60min, 75min and 90min with 25%, 50%, 75% and 100% replacement respectively. This study helps us to handle the travelling time of the mix in the site. [24]

IV. Hardened Properties Of Rap Inclusive Concrete

Hardened properties of concrete indicate the quality of the cement concrete in an effective way. Similar to the fresh properties of the concrete mix, the hardened properties of the concrete mix also depend on the gradation of the aggregates, shape of the aggregates, cement paste and water cement ratio etc., some of the hardened properties of the concrete are namely the compressive strength, split tensile strength and flexural strength. Apart from the above properties, importance is also given to the properties like toughness, permeability, acid resistance etc., the following chapters gives a detail explanation on the influence of RAP when replaced in proportions with natural aggregates.

IV.1. Compressive Strength

Compressive test on the hardened concrete is one of the basic and important tests to assess the quality of the concrete mix in terms of its strength. Based on many research studies it was understood that the compressive strength of the concrete reduces with the increment in the RAP replacement. [25] [26] [27] It was due to theweak bond between the aggregate and the cement paste in the presence of the asphalt film on the surface of the aggregate. The soft asphalt film would cause stress concentration which may ultimately results in micro cracks around the aggregate, this results in strength reduction in concrete containing RAP as aggregates. [5] [6]. It was found the same in the research study of "K.E. Hassan et al.". He stated that the concrete containing RAP has shown lesser compressive strength when compared with the control concrete mix containing natural aggregates. Based on his research study, the concrete containing coarse RAP has given pretty satisfied results when compared with the concrete containing both the coarse and fine RAP in replacement of natural aggregates. It was observed that the there is a strength reduction of 65% in concrete with coarse RAP, whereas 80% reduction in concrete containing both the coarse and fine aggregate in comparison with the control concrete mix at the age of 28 days. [2] [4] [24] [26] [28] [29] [30]

It was observed from many research studies that the concrete specimens containing RAP has shown less cracks at failure when tested under compressive loading compared with the control mix containing natural aggregates. This behavior was mainly due to the asphalt motor coating around the aggregate. It was proven in some of the research studies that the concrete containing both the coarse and fine RAP provided the strength of less than 44 MPa at 28 days of curing [1].

IV.2. Flexural Strength

Flexural strength values of the RAP inclusive concrete also shown a similar behavior as that of compressive strength values. The trend in reduction of strength was also similar [27] i.e., the strength decreases with an increment in the percentage of RAP content in the concrete mix. But the RAP aggregates showed a better performance than the concrete mix containing natural aggregates in terms of load absorption. It was noticed that the concrete containing coarse RAP has showed reduction in strength up to 35% in comparison with control concrete and the concrete containing both coarse and fine RAP has showed a reduction in strength more than 45%. Based on research findings on flexural behavior of concrete specimens containing RAP, it was noticed that the specimens containing natural aggregates fail in an explosive way whereas the specimens containing RAP fails slowly in comparison with concrete with natural aggregates. This behavior might be due to the asphalt film present in the RAP aggregates. This asphalt film reduces the elastic modulus of the concrete containing RAP by enhancing the specimens to absorb more loads than the concrete containing natural aggregates. [1] [2] [23] [24] [26] [28]

IV.3. Split Tensile Strength

Split tensile test is an indirect method used to determine the tensile capacity of the concrete specimens. As observed in the case of compressive strength, there was a similar trend of reduction in the tensile strength with increase in RAP content in the concrete mixes [27]. But the tensile strength values are way lesser compared

to the compressive strength of RAP inclusive concrete. It was stated in many research studies that the concrete containing coarse RAP are performing better among the concrete mixes containing both coarse and fine RAP and concrete mixes containing fine RAP alone. [2] [4] [5] [6] [24] [26] [28] [29] [30]

IV.4. Toughness

Toughness is one of the key properties in the concrete applications where the loads are of cyclic and impact in nature. When such cyclic and impact loading are expected, the concrete must have higher strain values to withstand such loadings effectively. It was found by various research studies that RAP inclusive concrete has shown better results in comparison with concrete containing natural aggregates. It was stated that as the RAP content increases, the toughness value of the concrete also increases in proportion with the increment of RAP i.e., higher the RAP, higher is the toughness. As an evidence to this statement, it was found that when different concrete specimens with and without RAP aggregates were tested under compressive loads, the specimens without RAP has failed with a clear visibility of crack formations whereas the specimens with RAP has very minute cracks. Hence by this observation we can assess that the asphalt film around the aggregate is enhancing the concrete to withstand higher strains, which helps in concrete applications where the loads are of cyclic and impact in nature. [5] [6].

When a comparison between coarse and fine RAP has made with regards to the toughness, it was found that the concrete containing only fine RAP has shown results similar to that of the concrete containing natural aggregates. But the concrete mixes containing coarse RAP has shown higher absorption of loads [43]. By this we can clearly state that due to the presence of more dust particles in fine RAP, the toughness values are very low. This is even shown the same in the fig.3

IV.5. Permeability

Looking into the research findings of "K.E. Hassan et al." it was understood that, with an increment in the RAP content in the concrete results in an increment in the permeability of the concrete mixes. It was found that the permeability of the concrete containing both fine and coarse RAP was higher than the concrete mixes containing coarse and fine RAP individually. When we look into the grain size analysis provided in the chapter-2, it was stated that the fine RAP was coarser than the fine aggregate, which means it results in permeable concrete when fine RAP is used in higher proportions where the voids may be higher in comparison with the concrete containing natural aggregates. As a solution to overcome this higher permeability in RAP inclusive concrete, Fly Ash can be used in certain proportions to fill the voids created by the RAP aggregates which helps to attain an impermeable matrix. It was also stated that when the concrete specimens containing RAP aggregates were heated to high temperatures, the asphalt present in the aggregates gets melted up and fills the voids created during the hydration, which ultimately helps in reducing the permeability. [1] [31] [32] [33]

IV.6. Acid Resistance

Based on acid resistance analysis on RAP inclusive concrete by "S. Singh et al.", it was found that the RAP inclusive concrete specimens gave less resistance to acid attack than compared to the concrete specimens containing natural aggregates. But the AT & BT treated aggregates gave satisfactory results when compared with untreated RAP inclusive concrete. But the acid resistance of concrete specimens went on decreasing even with the increment in the treated RAP. However to determine the effective behavior of RAP aggregates, the RAP inclusive concrete specimens were cured in 3 different environments like under normal water, HCl solution and H_2SO_4 solution. Among the three environments, the acid attack was more aggressive in the specimens which were exposed to H_2SO_4 solution. Along with this oven dry (OD) and saturated surface dry (SSD) conditions were also tested on these RAP inclusive concrete specimens. Among these two, it was found that the specimens under OD have experienced much degradation in acidic environment when compared with the SSD condition. [24]

V. Figures and Tables

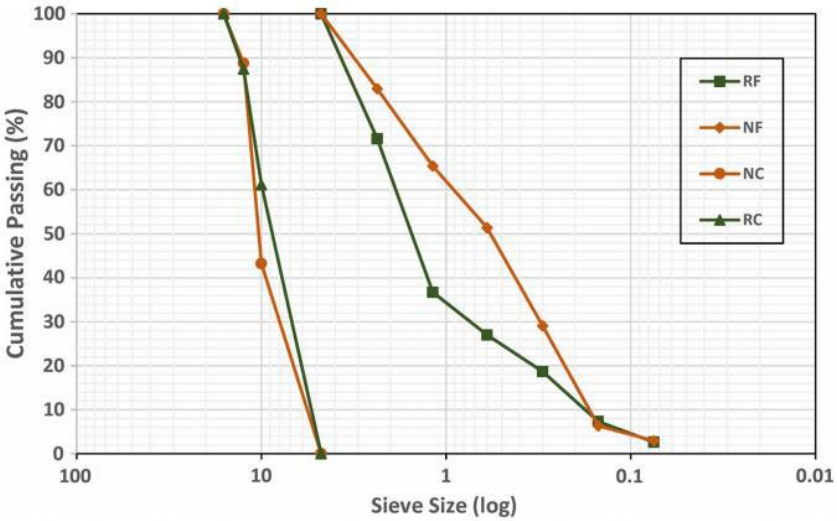

Fig.1 Grain size analysis of natural and RAP aggregates [31]

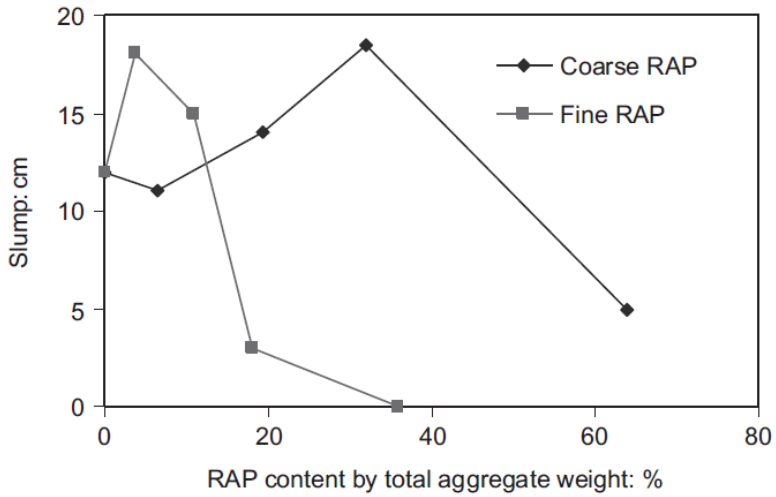

Fig. 2 Relation between slump and RAP content. [5]

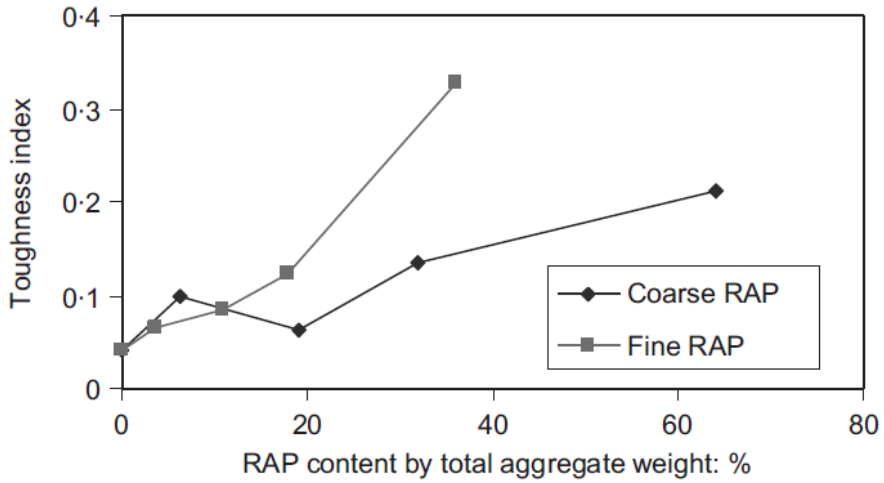

Fig. 3 Relation between Toughness index and RAP content. [5]

S. No	Country	Million tons of RAP
1	US	100
2	UK	11
3	European Countries	50
4	Japan	12
5	India	Approx. 100

Table 1 RAP production per year. [1] [2]

S. No	PROPERTIES	COARSE RAP	FINE RAP
1	Specific Gravity	2.2-2.6	2.2-2.6
2	Absorption (%)	1.8-2.9	1.8-2.8
3	Bulk density (Kg/m^3)	1940-2300	1600-2200
4	Crushing value (%)	16-20	-
5	Impact value (%)	4.3-33	-
6	Abrasion resistance (%)	18-30	-

Table 2 Physical and Mechanical properties of RAP. [34] [35] [36] [37] [38]

Element compound	Test result (% by weight)
SiO_2	38
Fe_2O_3	26.8
CaO	16.3
Al_2O_3	11
SO_3	2.9
TiO_2	1.8
K_2O	1.73
MnO	0.585
SrO	0.37
CuO	0.13
V_2O_5	0.11
BaO	0.2
Re_2O_7	0.06
ZrO_2	0.055
ZnO	0.045

Table 3 Chemical composition of RAP aggregates [19].

Mix proportion	Water / cement ratio	Slump (mm)	
		Gravel	RAP
1:2:4	0.50	70	33
1:2:4	0.60	84	45
1:2:4	0.70	100	74
1:3:6	0.50	41	17
1:3:6	0.60	50	30
1:3:6	0.70	80	40

Table 4 Workability of RAP inclusive concrete. [23]

VI. Conclusion

Based on several research observations the following conclusions were made regarding the utilization of RAP aggregates in concrete applications in replacement with natural aggregates.

1. The physical and mechanical properties of RAP aggregates were slightly lower than the natural aggregates. especially in case of sieve analysis, where the coarse RAP was finer than coarse aggregates and fine RAP was coarser than the fine aggregates. This was expected due to the milling process of the RAP aggregates and conglomeration of the RAP aggregates due to the presence of asphalt mortar. The specific gravity of the RAP aggregates was found to be less in comparison with the natural aggregates.

2. It was suggested that processed RAP aggregates have better performance than the unprocessed RAP aggregates. for example, the water absorption of unprocessed RAP was higher than the treated RAP aggregates.
3. As the RAP content increases the slump value of the concrete decreases when compared with concrete made of natural aggregates. This was due to the surface texture and shape of the RAP aggregates and also due to the presence of more dirt particles in RAP. When we observe the shape of the RAP aggregates, they are of mostly irregular and angular in shape which results in poor workability. And when a comparision study of slump was made among coarse and fine RAP inclusive concrete, it was found that only coarse RAP inclusive concrete has a better performance among the both.
4. When compressive strength analysis of RAP inclusive concrete has been made, it was determined that the strength of the specimens decreases with an increment in the RAP aggregates. this was due to the weak bond between the asphalt film around the RAP aggregate and the cement paste. But as a solution to this, treated RAP aggregates which are free from dirt has a better performance.
5. Similar to the compressive strength, the flexure and split tensile strength of the concrete specimens inclusive of RAP aggregates followed the same trend. But it was assessed that due to the presence of the asphalt film around the RAP aggregates, the load absorption of the concrete specimens increased in comparison with the concrete made of natural aggregates. This was due to the reduction in elastic modulus of the concrete with an increment in the RAP content.
6. Toughness index of the concrete containing the RAP aggregates gave a satisfactory result in comparison with the concrete containing natural aggregates. This proved that RAP inclusive concrete can be used where the loads are of cyclic and impact in nature.
7. The permeability of the concrete containing RAP is higher, which means the chance of corrosion of the reinforcement will be high when used. This was due to the gradation of the RAP aggregates and the fineness modulus of the RAP aggregates. As a solution to this problem, fly ash can be used to improve the permeability of the concrete when RAP aggregates are being utilized. [39] [40] [41] [42].

VII. Gaps Identified

After referring to several research studies, the following were some of the gaps which were identified when RAP was used as aggregates.

1. Even though there are many research studies on fly ash inclusive concrete with RAP as aggregates but there is no clear relation between fly ash and RAP aggregate proportions.
2. It was also found that there are very limited research studies on RAP inclusive geopolymer concrete. [39] [40] [41] [42].
3. No research study has provided a solution for the 100% effective use of RAP as aggregates in concrete because of its reduction in strength.

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