Review on applications of RAP in civil engineering

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Abstract. The use of "Reclaimed Asphalt Pavement" waste (RAP) has begun to be needful in different industries. These industries works need more development and new infrastructure construction. The roads, highways, airports, etc. are among these infrastructures. As a result, huge quantities of RAP waste are generated and require special processes including reuse and recycle. Such processes for RAP reduce the quantities of this waste and, also, reduce the consumption of the energy. Recycling RAP material has been utilized in a way that covers large civil engineering applications, e.g., roadbed layers, road surfacing, bituminous mixtures, road shoulders as embankment, back-filling material, retaining walls, slope protection, landfill capping systems, pothole filler material, and drainage works. In this paper, the definition of RAP, properties affecting the efficiency of the RAP, and factors controlling the recycling of RAP has been presented. Typical ranges and average properties of RAP has been summarized and presented. The applications of RAP in the construction of roadbed layers and the design of bituminous mixtures have been discussed with typical RAP contents. It appears that the basic properties of RAP are varied widely from country to others. RAP waste is accepted by civil engineers to improve roadbed layers and asphalt mixture design.

Keywords: Reclaimed asphalt pavements, Atterberg limit, specific gravity, compaction test, California bearing ratio.

1. Introduction
All over the world, each year maintenance of roads and highways produce millions of tons of milled asphalt and huge quantities of "reclaimed asphalt pavement" (RAP). Also, huge amounts of wastematerial are generated from the processes of road demolition. In the USA only, each year, the estimated quantities for the milled asphalt are more than 100 million tons [1]. Unfortunately, the reuse of these waste materials is not at the required level, the deposition and landfilling are the commonly used way to dispose these materials. In the last decade, many efforts have been tried to reuse or recycle different waste materials [2,3,54]. The application of recycling technologies maintains the standards of road service level, conserve natural resources, and has technical, environmental, and economic value [4-5]. They are incorporated in different civil engineering applications; therefore, large quantities of natural aggregates and good quality materials are saved, also, more space in landfills are provided [6]. Thus, in this review paper, the definition, description, and properties of RAP material have been reviewed and discussed as it is important to attract the attention of researchers, engineers, and contractors to the importance of RAP material and their suitability in civil engineering application.
2. Definition, properties and description of RAP

Kearney [7] defined the "reclaimed asphalt pavement" (RAP) as chunk materials from previously damaged road pavement. Also, "Reclaimed asphalt pavement" (RAP) is defined as a mixture of the removed pavement materials (asphalt and aggregates) [8]. Imad et al. [9] stated that the bitumen coated reclaimed aggregate is the RAP, and it is obtained from the surface of the failed pavement. Or, it is a material obtained from the pavement [4, and 10]. Also, the RAP is an aged asphalt obtained as a result of rehabilitation or maintenance of roads. The wastes of asphalt pavement are the source of RAP [11]. RAP can be obtained using milling to dredge the layer of the previous pavement [4 and 12]. In fact, two processes are conducted to recycle RAP from the pavement, they are milling, and crushing [13].

The aggregate in RAP is of a well-graded and high-quality type. It is asphalt cement coated [11]. There are important properties that affect the efficiency of the RAP. These properties include the moisture content, gradation of RAP, type of aggregate material that RAP contained, and the content and condition of bitumen it contained. These properties should be considered in the selection of the RAP [5, and 13]. The crushing (milling) type and asphalt mix type are factors that RAP properties are dependent on [11]. Many factors control the recycling asphalt materials. Some of these factors is controlled by the economy and other factors controlled by the environment. There are different approaches for recycling RAP, they depend on issues like requirements, and technologies [6, and 14]. RAP gradation is an important factor affects the efficiency of RAP. This factor controlled by the source of RAP or its characteristics (RAP durability, RAP stiffness and stability). Also, the milling technique (milling speed, the depth of milling, and milling rezone temperature) and field condition affects RAP gradation [13].

Mishra [15] proposed the ranges of typical RAP properties at which the typical compaction density, moisture content, asphalt content, and CBR value are (1.5 g/cm3 to 1.95 g/cm3), (3% to 5%), (5% to 6%), and (20% to 25%), respectively. Gupta et al. [16] showed that the variation in the angle of friction of RAP is (37 to 47) degrees. The statistical study of Xiao et al. [13] showed that the common range of asphalt content in RAP is ranged from 4% to 7.5%.

Based on the data from researches reviewed in this paper, Figures 1 to 5 shows the range of RAP properties. The properties shown in these figures are specific gravity, maximum dry density, optimum water content, CBR, and bitumen content. The RAP data in these figures are collected from different researches of different countries including the USA, Thailand, Indonesia, Singapore, Chile, Iraq, KSA, Iran, and Nigeria. The examination of these figures shows that the basic properties of RAP varied widely from country to others. The RAP materials are lighter than soil. They have specific gravity values ranges from 2.25 to 2.53 with an average value of 2.40. The maximum specific gravity is for RAP materials from Singapore, while the minimum value is from Nigeria. The compaction characteristics of RAP materials are presented in Figures 2 and 3. It is clear that the variation in density values is very wide, while it is lesser for optimum water content. The minimum, maximum, and average densities are 1500 kg/m3, 2220 kg/m3, and 1841 kg/m3, respectively. The variation in RAP compaction properties can be attributed to different sources of the main constituent of RAP, i.e. the aggregates. Again, very wide differences in the bearing values of the RAP materials are shown in Figure 4. The CBR with its minimum, maximum, and average values is 5%, 25%, and 15%, respectively. This can be due to the type of aggregate, and the age and the content of bitumen in RAPs. The CBR value, however, presented in literature is low for RAP material from some countries like Iraq, and vice versa for RAP from other countries like KSA. Finally, Figure 5 shows that the common range of bitumen content in RAP from different countries ranges from 2.9% to 7.5%, with an average value of 5%. Higher bitumen content is recorded for RAP samples from Thailand Chile.
3. Using RAP in road applications

The RAPs are used in road applications of low-specification, like the construction of roadbed layers. Hack and Bryan [28] stated that recycled asphalt materials can be utilized as a base-course material, also, it can be used in unpaved-roads as a road surfacing. In such applications, the use of recycled asphalt materials has benefits like road performance improvement, and prevent dust. Papp et al. [29] stated that RAP can provide a good application as a granular base material. Taha et al. [23] showed that the mixture of RAP-natural aggregates provides good roadbed layers. They mixed the natural aggregate with five different contents of RAP (from 20% to 100%). The properties of RAP used are asphalt content 5.5%, and CBR value 11%. They were concluded that the maximum RAP contents required for the construction of the sub-base layer and base layer are 60% and 10% respectively. While, according to McGarrah [30], the maximum RAP content required for the construction of the sub-base layer is 50%. On the other hand, 25%, 50%, 75%, and 100% RAP was used by Cooley [31] to improve the properties of two types of aggregate (surrounded and angular). This author found that the CBR values are inversely proportional with RAP content. Gregory and Halsted [32] investigated the possibility of the RAP full-depth reclamation to produce a new base layer. Studies recommended...
the use of unbound RAP in asphalt pavement layers. The typical content of RAP in such construction is between 20% and 50% [21].

RAP material can be treated with different additives. RAP properties can be restored using some types of additives like soil/lime, cement, bitumen emulsion, etc. The use of these additives is not aimed only to restore the RAP properties, but it has many environmental benefits. Mohammad et al. [24] used foamed asphalt to treat RAP and studied the potential of the treated RAP as a roadbed layer. They recommended the treated RAP with minimum asphalt content of 1.5%. Different additives have been used for RAP full-depth reclamation (asphalt emulsion, foamed asphalt, cement, and lime-fly ash). Soil and RAP mixtures treated with cement have been used by Suebsuk et al. [19]. These authors proved that the treated mixtures can be used in the construction of pavement layers (base and sub-base). They tried to increasing the strength and decreasing the deformation of soil and RAP mixtures by creating them with cement under curing. According to Mishra [15], the replacement of the natural aggregate with 30% of RAP produces a mixture suitable for the base course pavement layer. Ansori and Radam [4] combined different content of RAP (from 3% to 100%) with natural aggregate to produce a suitable combination for use in roadbed layers. They found that the combination of RAP and aggregate reduces the specific gravity and CBR values. However, a combination of 3% and 9% of RAP with aggregate is necessary to meet the requirements of the base course and sub-base layers, respectively.

Also, RAP can be used for road shoulders as embankment, back-filling material, retaining walls, slope protections, landfill capping systems, pothole filler material, and drainage works [4, 10, 11, and 12]. The environmental impact of RAP has been investigated by Yang et al. [12]. The engineering possibility of using RAP in an unbound road, also investigated. The result of this investigation proved that the RAP can be utilized as an unbound material even in acidic environment [12]. An economical solution was stated by Troeger and Widyatmoko [33] to reuse and recycle the "distressed asphalt surface courses". These authors showed that the lightly traveled roads, footways, and other rural and urban sites are possible sites to recycle and reuse of these materials. The solution includes pulverizing the existing roads to a suitable depth, producing a uniformly-graded material, milling broken up and levelling the surfacing layers, applying bitumen emulsion, then rolling the surface and completing the surface layer.

Recycled asphalt materials can be used as primary aggregates in bituminous mixtures [6]. RAP materials can be recycled and reused as bituminous materials by adding these wastes into the asphalt mixtures [6, and 19]. The asphalt or bituminous material comprises, mainly, aggregates (80% to 95%). In addition, it comprises 2% to 8% filler and 3% to 7% binders. The constituent which provides the skeleton, and as a result, the mixture stability, is the aggregates [6]. The thickness of the bituminous material layer varies from 5 cm to 60 cm [34]. In other words, huge quantities of natural aggregates are required for the construction of road pavement. Studies [35-38], incorporated the RAP materials in the design of hot mix asphalt. Researchers stated that the including of RAP in asphalt mixture decreases the mixing temperature without affecting the mixture's performance. In other words, the including of RAP helps in increasing the indirect-tensile-strength, and stiffness, also, it may increase or decrease moisture susceptibility, and decrease rutting potential and fatigue resistance. Furthermore, the utilization of RAP materials in asphalt mixture applications has a number of environmental benefits including reducing the impacts of these materials and energy needs. In addition to these benefits, the utilization of RAP material helps in decreasing the consumption of bitumen and natural aggregates used in the asphalt mix design [26, 38, 39, 40, and 41].

However, there is a key consideration that should be taken into account in the design of the mixture. It is the water content of RAP at field. Also, the activity of RAP's bitumen binder should be evaluated, as a visual inspection may serve in such evaluation. The color, brittleness, and shining of the RAP can be noted, the dark grey color is an indication of inactive bitumen binder. The brittleness and missing of shining are other indications of the inactive bitumen binder. To increase the consumption of the huge RAP quantities, materials with higher content of RAP should be investigate. The major properties of asphalt can be affected by the grading and source of RAP [13, and 42]. On the
other hand, the fine particles found in RAP can be used directly to mix with the new asphalt binder. These particles can be separated from RAP materials using sieving. The materials which range in diameter from 0.15mm to 0.30mm are the "fine particles" [13, 43, and 44].

In some countries, there are limitations to the amounts of RAP used in different road layers. The maximum amount of RAP in the surface course is 10%, while in other layers (binder-course and base) it is 50%. For countries which use Superpave mixes, the maximum allowable RAP content in the surface course is 10% to 15%, and 50% in the other layers [45]. In Indonesia, the upper limit of RAP that allowed to use in the design of "hot mix asphalt" is 15% [46]. In the USA, 20% of RAP is traditionally used for the wearing layer, while the content of RAP in the binder layer is 30% [47-48]. Whereas some European countries allowed more RAP content. In these countries, 50% of RAP is allowed for a new base layer [40, and 49]. López et al. [26] recommended 44% RAP content to construct the warm-mix asphalt pavement.

4. Using RAP in soil stabilization

Different efforts have been directed to investigate the possibility of RAP to stabilize soil. Some efforts studied the potential of using RAP alone, while other efforts used admixtures with the RAP [20, 38, 50, and 51]. The cohesive soil stabilized with RAP and cement was studied [18]. These authors showed that the stabilized soil with 2% cement satisfies the requirement of pavement layers. One problematic lateritic soil (clayey sand) from Thailand has been stabilized by adding RAP and cement with different content [19]. The content of RAP used is 20%, 40%, 60%, and 80%. It was noted that the RAP (up to 50%) decrease the optimum water content of the soil. The strength of soil-RAP is increased with cement content and curing period. An attempt to stabilized clay soil was carried out [52]. In this attempt, the RAP and bagasse ash have been used to stabilize the soil for pavement construction. It was noticed that 40% of RAP increase the dry density of the soil from 1.77 g/cm3 to 1.79g/cm3. The addition of 4% bagasse ash to the mixture increased the density to 1.82 g/cm3. The content of bagasse ash required to improve the bearing value of the mixture of soil and RAP is 6% to 8%. Kamel et al. [5] evaluated the California bearing ratio for subgrade soil mixed with different proportions of RAP material (from 0% to 100%). The content of bitumen in RAP used is about 5 %. They noted that the RAP increased the maximum dry density from 2.155 g/cm3 to 2.212 g/cm3 and decreased the optimum water content from 5.8% to 4.6 %. They also noted an increase in the CBR value. The compaction and strength of cohesive soil stabilized with RAP (contains 5.99% bitumen) have been studied by Alhaji and Alhassan [22]. They have noted an increase in maximum density from 1890kg/m3 to 2036 kg/m3 for soil mixed with 30% RAP. At this RAP content, the CBR value increased from 11% to 35%. The clay of low plasticity mixed with different percentages of RAP has been studied by Alhaji et al. [20]. They have noted an increase in mixtures density as a result of improving the grading on these mixtures by adding RAP. Also, the addition of RAP made the soil suitable to the requirements of the sub-base layer, while the requirements of the base course layer required an additional 2% cement to the mixture of soil and RAP. However, the stabilization of cohesive soil using RAP material is highly affected by the type of aggregate contained in the RAP used. The maximum density of the cohesive soil stabilized using RAP of high specific gravity aggregate can be increased clearly [53].

At the end of this review, it is worthwhile to summarize the maximum amount of RAP used in different road layers as shown in Table 1.

| Refences | [4] | [15] | [19] | [22] | [23] | [30] | [40] | [45] | [49] | [51] |
|----------|-----|------|------|------|------|------|------|------|------|------|
| Maximum RAP % Subgrade | - | - | 50 | 30 | - | - | - | - | 40 | |
| Maximum RAP % Subbase | - | 50 | - | - | 60 | 50 | - | 50 | - | - |
| Maximum RAP % Base | 9 | 30 | - | - | 10 | - | 50 | 10 | 50 | - |
5. Conclusions
This paper reviews and discusses different applications of the "Reclaimed Asphalt Pavement" (RAP). Every year, huge quantities of RAP waste are generated and require special processes including reuse and recycle. This review aims to attract the attention of researchers, engineers, and contractors to the importance of RAP material and their suitability in civil engineering applications. Accordingly, important points have been highlighted. RAP is an aged asphalt, it is obtained (as a result of rehabilitation or maintenance of roads) by milling and crushing. The selection of the RAP and its efficiency are affected by its moisture content, its gradation, type of aggregate material, the content type and condition of bitumen, and the crushing (milling) technique. Typical common range from lower to up and average values of RAP properties are proposed as follows: specific gravity 2.25 to 2.53 and 2.40, maximum density 1500 kg/m³ to 2220 kg/m³ and 1841 kg/m³, optimum water content 3% to 8% and 5.7%, CBR 5% to 25% and 15%, bitumen content 2.9% to 7.5% and 5%. Recyclimg RAP materials are utilized in a way that covers large civil engineering applications, e.g., roadbed layers, road surfaceing, bituminous mixtures, road shoulders as embankment, back-filling material, retaining walls, slope protection, landfill capping systems, pothole filler material, and drainage works. There are limitations to the amounts of RAP used in different road layers. The maximum amount of RAP in the subgrade, sub-base, and base layers is 50%, while in the surface course the lesser amount of RAP is allowed. RAP material can be treated with different additives. RAP properties can be restored using different additives like soil/lime, cement, bitumen emulsion, etc.

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