Construction and Building Materials 173 (2018) 419–428

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Resonant column testing on Portland cement concrete containing recycled asphalt pavement (RAP) aggregates

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ARTICLE INFO

Article history:
Received 7 November 2017
Received in revised form 11 March 2018
Accepted 28 March 2018

Keywords:
Portland cement concrete
Recycled asphalt pavement
Compressive strength
Air entrainment
Workability
Elastic modulus
Resonant column
Non-destructive testing

ABSTRACT

This study deals with material properties of Portland cement concrete (PCC) made with aggregate that is replaced with recycled asphalt pavement (RAP). A series of PCC mixtures were produced and tested in uniaxial compression using RAP aggregate as substitute of fine and coarse natural aggregate. The main variable was the percentage content by weight of RAP aggregates in the concrete mixture. Both fresh and hardened properties of concrete were examined. Moreover, a relatively new non-destructive technique (free-free resonant column – FFRC) was used to measure concrete's elastic modulus. The experimental results indicate that the compressive strength and the elastic modulus decrease with increasing RAP aggregate replacement, while all mixtures containing RAP aggregates remain workable. Additionally, the replacement of fine natural aggregates has a more pronounced effect on the examined properties. Finally, the FFRC can provide good estimation of elastic modulus.

1. Introduction

In part of the ongoing recycling efforts, most transportation authorities are attempting to reduce solid waste generation. Accordingly, the agencies are evaluating every prospect to use or reuse waste materials. Due to the high volumes of concrete produced every year for construction projects, the amount of aggregate used for concrete production is extremely high in terms of volume. The feasibility of incorporating recycled materials in concrete has started being evaluated by several researchers [1–3]. Previous research has successfully used fly ash [4], silica fume [5] and other inorganic waste materials in concrete [1]. Moreover, previous studies investigated the use of waste tires in concrete and they focused on two types of rubber byproducts crumb rubber and tire chips [3,6]. The results have shown that the inclusion of recycled rubber as aggregate in concrete mixtures results in concrete with lower compressive strength but with higher toughness and ductility. These properties allow concrete to be a more effective material in some structural applications.

Highway agencies throughout the world are faced with problems associated with disposal of millions of cubic yards of deteriorated asphalt pavement every year. As a result, the interest in recycling procedures is increasing in Europe [7] and worldwide [8], and many agencies are becoming interested in developing new opportunities to use recycled asphalt pavement (RAP) in construction products. The most important reasons for using RAP as an aggregate replacement in concrete mixtures are the following:

- The growing shortage of landfill space creates a need to recycle as many materials as possible.
- The use of RAP aggregates would slow the depletion of high quality natural aggregates.
- The scarcity of local natural aggregates will necessitate obtaining them from other locations. This will increase transportation and manpower costs that will eventually result in an overall increase of cost.
- Existing roads would be suitable nearby quarries, eliminating long-distance transportation costs, and thus decreasing delivery time.

Several researchers started investigations on the feasibility of using RAP in lieu of conventional aggregate in concrete mixtures [9–15]. The first studies suggested that replacement of relatively small amounts of aggregate with RAP results in only minor decrease in strength, and that workability may actually be enhanced by this substitution [15]. For transportation and other agencies to benefit from the cost and environmental advantages of this technology, it would be desirable to use large percentages of RAP in lieu of virgin

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https://doi.org/10.1016/j.conbuildmat.2018.03.256
0950-0618/

aggregate in concrete mixtures. Recent studies [9,11,16,17] also indicate that the addition of RAP in concrete reduces the compressive and tensile strength as well as the elastic modulus. These properties decrease with an increase in the percentage of incorporated RAP. Also it is mentioned that the inclusion of RAP aggregates leads to a decrease of workability [11]. This can be attributed to the weak adhesion between the asphalt content of the RAP aggregate and the cement paste. It is known that asphalt is a hydrophobic material and therefore the absence of water in the transition zone around the aggregates may only weaken the mechanical properties of concrete [18]. Since the interfacial transition zone is affected by the size of the aggregates, two different types of mixtures were examined in this study. More specifically, in one type only the fine aggregates were replaced with percentages up to 100% ratio while in the second both fine and coarse aggregates were replaced but in smaller percentages (from 5% to 15%).

In this article both fresh and hardened concrete properties were investigated. The properties that were investigated are: workability, entrained air, compressive strength, elastic modulus and maximum strain at failure. Density, or unit weight, is also an important property and was measured in the course of this research project although it could be easily predicted. Furthermore, a relatively new technique based on the free-free resonant column (FFRC) was utilized to measure concrete's elastic modulus and the results were compared to the ones obtained using destructive testing (uniaxial compression tests). The FFRC is a state-of-the-art nondestructive technique, which is described in detail by Nazarian et al. [19]. It is a seismic test in which a cylindrical specimen is subjected to an impulse load at one end. Compression waves spanning a range of frequencies propagate within the specimen and are received by an accelerometer at the other end. By analyzing the resonant frequencies, the modulus of the specimen can be determined based upon the principles of wave propagation in a solid rod. The advantages of this method include the fact that it is a nondestructive test and that in less than 3 min a specimen can be tested and results generated via a computer program. It should be noted that for each of the eleven tested mixtures nine concrete specimens were made, in order to get a significant sample for statistical analysis.

The compressive strength of Portland cement concrete (PCC) is its most important material parameter and is used through various formulas in all concrete design codes [20,21] to such an extent that compressive strength and density are almost the only concrete material properties considered by designers. The primary technical objectives of this study are to evaluate the FFRC test in RAP-PC and to quantify the effect of high fine RAP to natural fine aggregate ratios on mechanical properties. According to the author's knowledge it is the first time that FFRC testing was performed on PCC containing RAP aggregate. Moreover, the large number of tested cylinders will provide a larger database for statistical analysis compared to previous studies that typically included a limited number of test specimens. Therefore, the presented data will be of great interest to the construction materials research community.

2. Materials and methods

The material properties of compressive strength, elastic modulus, strain at failure, air content and workability were quantified with changes in the RAP content. The main variable investigated in this research phase was the level of aggregate replacement. Whole (coarse & fine) and fine RAP was used to substitute between 5 and 100 percent of the weight of appropriately sized aggregate constituents in the mixture. A series of concrete mixtures using different percentages of RAP aggregate was identified.

For each mixture nine cylinders with dimensions of 100 mm by 200 mm were cast and tested in uniaxial compression after seven days. The cylinders were tested in uniaxial compression in order to determine their compressive strength, modulus of elasticity and strain at failure. For each specimen before the destructive testing, the free-free resonant column (FFRC) technique was used to determine the modulus of elasticity.

2.1. PCC mixtures and RAP properties

A total of 11 mixtures were made including the control mix. The control mix of this research program was designed with a mixture ratio for "cement: water: sand: coarse aggregate" of 1.0: 0.45: 1.2: 2.0 by weight.

This mixture yielded an average 28 days compressive strength of 34 MPa. In the concrete mix, a type I/II Portland cement was used. The fine aggregate had a specific gravity of 2.7 and fineness modulus of 2.8. The coarse aggregate had a specific gravity of 2.65 with a maximum aggregate size of 13 mm.

The Recycled asphalt pavement (RAP) material was donated by a local supplier. The maximum aggregate size of the RAP used was also 13 mm. Physical and mechanical properties of the RAP aggregates are shown in Table 1.

The whole RAP (coarse and fine) was substituted into the concrete mixture in place of the whole natural aggregates (coarse and fine) at weight percentages of 5%, 7.5%, 10%, 12.5%, and 15%.

Also, fine RAP (RAP aggregates that passed through the 2.36 mm sieve) were substituted in the concrete mixture in place of fine aggregates by weight percentages of 20%, 40%, 60%, 80%, and 100% of natural fine aggregate. There were no admixtures used in these mixtures. The proportions of the materials that were used in the control mixture are detailed in Table 2, while the gradation of the coarse aggregates is shown in Table 3.

The following abbreviations are used to distinguish between the different mixtures:

- F.RAP stands for Fine RAP replacement only, which means that only fine aggregates of the control mixture were replaced by fine RAP (RAP sieved through the #8 sieve) (Fig. 1).
- W.RAP stands for the Whole (fine and coarse) RAP replacement, which means that both the fine and coarse aggregates of the control mixture were replaced by fine and coarse RAP aggregate.

RAP, as well as, natural aggregates was originally sieved through the (12.7 mm, 9.5 mm, 4.75 mm, 2.36 mm, 2.00 mm, 0.60 mm, 0.42 mm, 0.3 mm, 0.15 mm, 0.075 mm) sieves. The RAP percent retained was calculated for each sieve. The substitution was performed according to the weights retained in each sieve, in order to achieve a direct replacement of the natural aggregate.

For example, for the replacement of the coarse and fine aggregates with 5% W.RAP (coarse and fine) the following calculations took place. The total weight of aggregates was 46170 gr. (% Coarse = 62.5%,% Fine = 37.5%). Thus, 5% of the total weight of the aggregates is 5% $\times$ 46170 = 2309 gr. The detailed calculations are shown in Table 4, where the last two columns are showing the exact amounts of aggregates used in the mixture.

Table 1
Properties of recycled asphalt pavement (RAP).

RAP properties	
Unit Weight	2150 kg/m^3
Moisture Content	5%
Asphalt Content	5.1%
Asphalt Penetration	30 at 25 °C (77°F)
Absolute Viscosity or recovered Asphalt Cement	13,000 P at 60 °C
Compacted Unit Weight	1800 kg/m^3
California Bearing Ratio (CBR)	25%