Construction and Building Materials 164 (2018) 1–11

Contents lists available at ScienceDirect

Construction and Building Materials

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

Assessing recycled pavement concrete mechanical properties under joint action of freezing and fatigue via RSM

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HIGHLIGHTS

- The RSM was used to assess the mechanical properties of PRAC under the joint action of freezing and fatigue.
- The number of fatigue iterations influences flexural strength, while freeze-thaw cycles influence compressive strength.
- The interaction between fatigue iterations and freeze-thaw cycles substantially impacts the relative dynamic modulus of PRAC.

ARTICLE INFO

Article history:
Received 5 August 2017
Received in revised form 17 December 2017
Accepted 27 December 2017

Keywords:
Pavement recycled aggregate concrete
Freeze-thaw cycles
Fatigue properties
Mechanical properties
RSM

ABSTRACT

Sample pavement recycled aggregate concrete (PRAC) was prepared with waste pavement concrete from an airport in China in this study. Frost resistance and fatigue performance were analyzed by comparison against common pavement concrete. The response surface method (RSM) was used to assess the mechanical properties of PRAC under the joint action of freezing and fatigue. Design Expert and Center Composite Design (CCD) software were applied to analyze the influence rules dominating freeze-thaw cycles, fatigue iterations, and their joint action in regards to the flexural strength, compressive strength, and relative dynamic modulus of PRAC with corresponding RSM models. The three RSM relation models were fit well and effectively represent PRAC characteristics after a series of fatigue and freeze-thaw cycles. The number of fatigue iterations appears to influence flexural strength, while freeze-thaw cycles influence compressive strength; the interaction between fatigue iterations and freeze-thaw cycles substantially impacts the P_n of PRAC.

1. Introduction

Airport transportation facilities are a crucial component of the national economic development as well as an important infrastructure for national security. In China's and many of the world's airports, concrete is the most common pavement building material. Building an airport requires a massive amount of raw material – the construction of a single average airport facility necessitates more than 10,000 cubic meters of cement concrete, of which aggregate stone accounts for more than 75%. Airports built since the emergence of "new China" exist within the context of rapid advancements in the national economy and must be continually renovated, altered, and expanded to meet today's demands [1].

Updating China's airports is a highly challenging endeavor for several reasons. Making alterations to a given airport results in a large amount of waste concrete. Further, covering old pavement raises the elevation of the surface and requires expensive alterations to the surrounding soil area and drainage works to accommodate the changes. Airports are typically located at a considerable distance from the natural aggregate yard, so transporting aggregate material also tends to be very costly. Further, continued mining of natural aggregate at our current rate threatens environmental damage, resource depletion, and serious harm to the ecological environment. The effective utilization of waste concrete produced by old pavement to create recycled aggregate that can be broken, cleaned, and screened into pavement concrete is not only convenient and cost-effective, but energy-efficient and eco-friendly [2].

Recycled aggregate concrete (RAC) is material prepared from old concrete after crushing, cleaning, sieving, and matching appropriate proportions to produce "recycled aggregate" as a replacement for part or all of the natural aggregate [3]. RAC is a new type of concrete that is well-suited to the demands for green production and operation [4,5], which has made it a popular research subject; previous studies have shown that the compressive strength and elastic modulus of recycled concrete are inferior to those of plain concrete [6–10] under the same water-cement ratio.

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https://doi.org/10.1016/j.conbuildmat.2017.12.219
0950-0618/

Further, the mechanical properties decrease as the percentage of recycled aggregate increases [11–13]. Recycled aggregate has been used in real-world engineering projects, most of which have centered around the compressive strength of concrete as the evaluation criteria [14]. This may not be suitable for airport pavement concrete, however, due to notable differences in the mixture design and application environment. Unlike reinforced concrete, airport pavement concrete is generally not equipped with steel. It also is subjected to heavy bending stress produced by aircraft wheel loads, making it especially susceptible to shrinkage cracks. It must be exceptionally durable, as well, to withstand freezing and thawing, corrosion, wear, and other aspects of the environment in which it is installed.

Research on RAC has also centered mainly around single factor performance. There have been numerous studies on freezing-thawing in regards to the material's resilience, but few on the mechanical properties of concrete after freeze-thaw cycles. Concrete fatigue performance research usually focuses on material fatigue deterioration laws, fatigue equations, and prediction models [15–21], while the mechanical properties of concrete after fatigue damage are rarely examined and the actual conditions of the pavement environment are not necessarily taken into account. Concrete is not destructed through a single factor, however – for example, the fatigue load generated by aircraft wheels and freeze-thaw cycles produced in the northern part of China often appear simultaneously. There has been relatively little research on the multi-factor effects acting upon pavement RAC.

The response surface method (RSM), which combines mathematics and statistics, was adopted in this study. RSM not only reflects the influences of various test variables on indexes, but also the influence of interactions among variables via 3-D images. RSM is often applied in agriculture, biology, food, chemistry, manufacturing, civil engineering, and other fields [22–27].

This study was conducted to assess, under the actual working conditions of airport pavement, the frost resistance and fatigue performance of plain pavement concrete (PPC), pavement recycled aggregate concrete (PRAC), and pavement natural aggregate concrete (PNAC) with the same mix proportions. We used RSM to investigate the mechanical properties of PRAC under the combined action of freeze-thaw and fatigue cycles as well as the interaction between the two factors. We hope that the results presented here provide a workable theoretical basis and technical support for the application of PRAC.

2. Test materials and methods

2.1. Raw materials

The cement we used to prepare specimens was P.O. 42.5 plain Portland cement with a density of 3.10 g/cm^3, a cement fineness of 1.6%, 3-day and 28-day flexural strength of 6.41 MPa and 8.94 MPa, and 3-day and 28-day compressive strength of 29.7 MPa and 51.7 MPa, respectively. The fine aggregate we used was river sand with a continuous gradation and particle size $\leq$5 mm, an apparent density of 2630 kg/m^3, and a fineness modulus of 2.78.

Two types of coarse aggregate were used in this study. First, natural coarse aggregate (NCA) and limestone gravel with three grades of gravel particle sizes, 5–10, 10–20, and 20–40 mm. The mass ratio of the NCA we used is 1:3:6, its apparent density is 2750 kg/m^3, and its bulk density is 1690 kg/m^3; the elongated and flaky particles content is 4.9% and its crush index is 8.9%. The other coarse aggregate was recycled coarse aggregate (RCA), which was provided by an airport in China at three grades of gravel particle sizes, 5–10, 10–20, and 20–40 mm. The mass ratio of the RCA we used is 1:3:6, its apparent density is 2540 kg/m^3, its bulk density is 1425 kg/m^3, its elongated and flaky particle content is 4.1%, and its crush index is 9.5%. Other properties of the RCA are shown in Table 1.

We used Ⅱ fly ash produced in Shaanxi Weihe River, P.R. China. A polycarboxylic acid and air-entraining water reducer were used with a water reducing rate of 20–35% and air entraining content of 3–5%. Tap water was used for this experiment with the chemical components listed in Table 2.

2.2. Test mix proportions

Airport pavement concrete must have flexural strength of 5 MPa or more. We used a total of three different mix proportions in this test: PPC, which consisted of cement, aggregate, and water, and PRAC and PNAC, which had the same water-cement ratio, sand percentage (SP), and admixture content. In the PRAC, the replacement rate of recycled aggregate for natural aggregate was 100% – the NCA in the PNAC mixture was completely replaced by the same volume of RCA. The PPC mix design we used is representative of most of China's airport pavement concrete, so we used it as a blank control group for comparison with PRAC. We sought to determine whether the properties of PRAC are superior to that of PPC. PNAC was mainly used to compare the differences in performance between pavement concrete made by RCA and NCA under the same mixture ratio.

The mix proportion, workability, and strength of the pavement concrete samples are listed in Table 3.

We found that the compressive strength and flexural strength of PRAC are higher than those of PPC, and all samples meet the relevant design requirements though they are lower than those of PNAC. This may be because the recycled aggregate has some cracks, voids, and other defects to which flexural strength is very sensitive. The compressive strength of PRAC is slightly lower than that of PNAC, as the strong compressive stress exerted in the test itself closed a portion of the internal cracks and pores of the concrete; the compressive strength of the material is not that sensitive as flexural strength to the cracks, voids, and other defects inside the concrete.

2.3. Specimen preparation and test method

We prepared specimens based on the Chinese standard "Standard for test method of mechanical properties on ordinary concrete" (GB/T 50081-2002) and "Standard for test methods of long-term performance and durability of ordinary concrete" (GB/T 50082-2009), and according to Lemaitre and L.C. Cai [25]. A typical specimen for damage mechanics tests must be small enough in

Table 1
Properties of recycled coarse aggregate.

Properties		Recycled coarse aggregate
Grain composition (%)	Pure aggregate	24.4
	Mixture	57.7
	Pure mortar	17.9
Apparent density (g/cm^3)		2.54
Ratio with NCA (%)		92
Bulk density (kg/m^3)		1425
Ratio with NCA (%)		84
Aggregate density	Apparent density (g/cm^3)	2.75
	Bulk density (kg/m^3)	1690
Water absorption	Water absorption of 30 min/relative water absorption over 24 h (%)	1.8/82
	Water absorption over 1 h/relative water absorption over 24 h (%)	2.0/90
	Water absorption over 24 h	2.2