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A case study on a cement treated RAP containing asphalt emulsion and acryl polymer

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ABSTRACT

A Korean contractor developed and used a cement treated Reclaimed Asphalt Pavement (RAP) containing asphalt emulsion and acryl polymer as base layer in Korea. Unfortunately, it was reported that the performance of the mixture was controversial by appearance of reflective and other cracking on the surface of the pavement. In the phase one study, main goals were evaluation of some mechanical properties as well as understanding the material category of this mixture. To achieve these goals, a series of literature reviews and laboratory tests were carried out including Marshall stability and flow, indirect tensile strength, water sensitivity, rutting resistance and compressive strength of both “Contractor mix” and Rhode Island (RI) pavement materials i.e. typical hot mix asphalt (HMA) and Portland Cement Concrete (PCC). According to the Asphalt Pavement Analyzer (APA) test results, it was observed that “Contractor mix” behaved similar to an elastic material at low temperatures while it tends to behave like a visco-elastic material at high temperatures to some extent. Also, it was resistance enough against the moisture damages and rutting phenomena, however, showed considerably lower compressive strength compared to PCC. Because of low compressive strength and probably high shrinkage of this mixture, it could be problematic to use it as base layer material and could affect pavement resistance against some distresses, particularly transverse and reflective cracking. Finally, because of high cement content and rigid behavior it was decided to model this material as concrete and/or cement treated RAP material in the second phase of this study.

1. Introduction

For more than a century, Hot Mixed Asphalt (HMA) has been used for paving roads and streets. Since the mid twentieth century, transportation organizations have recycled old broken asphalt mixtures for reuse, instead of disposing the asphalt mixture in landfills [1]. In the 1970′s, these organizations recycled more HMA than ever before because oil prices increased and access to high quality aggregates became more difficult. When old or distressed asphalt concrete is recycled, it can

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qualify for reused in asphalt pavement layers [2]. Recycled Asphalt Pavement (RAP) is generated by milling partial or full depth asphalt pavement scheduled for removal.

RAP is viewed as a valuable resource because of the high quality of its aggregates and asphalt binder. But at times, RAP must be modified to meet the requirements for the binder and aggregate specifications. First, the asphalt content may not be sufficient for making a new asphalt mixture, and on the other hand, because of exposure to weathering and sun light, the old asphalt binder is usually more brittle than a newer one. Therefore, adding some rejuvenators or additives, e.g., emulsions can compensate for these deficiencies. Secondly, because of milling and crushing operations during the asphalt pavement removal process, RAP aggregates do not contain enough coarse aggregate. Adding some additional virgin coarse aggregate can not only meet the grading requirements, but also improves the quality of aggregates [3]. Thirdly RAP modifications can be accomplished by the addition of some stabilizer or additives such as Portland cement and Polymeric additives etc. These materials can change quality of RAP mixture by improving the mechanical properties and decreasing the moisture sensitivity of mixture.

Asphalt emulsion and foamed asphalt are the most common materials used in cold recycling of asphalt pavements. These emulsions which make it feasible to recycle old asphalt concrete at lower temperatures at the plant or in place, and these processes are called Cold Central Plant Recycling and Cold In-Place Recycling, respectively. The cold recycling methods lead to more economic, environmental and construction benefits in comparison with hot recycling method. One of additives, which could be added to RAP, is Portland cement. Portland cement looks promising to improve mechanical properties of cold recycled asphalt concrete because of the following reasons [4]:

- Portland cement accelerates curing process of emulsions in cold recycled asphalt mixture.
- Portland cement increases viscosity of binder.
- Portland cement binder probably increases resistance of mixture against compressive stresses in comparison with neat asphalt binder.

However, Portland cement and asphalt emulsion have different basis, and their bond and interactions may lead to deficiencies in the produced mixture. Another issue which could be controversial for this mixture is, understanding its behavior at different temperatures. Pavement designers need to know properties of materials to be able to predict their behavior under different pressures and temperature. Mixture containing both asphalt emulsion and Portland cement could be hard to predict, because Portland cement is an elastic material and its mechanical properties are almost independent to the changes of temperature, while, asphalt is a visco-elastic material that its physical and mechanical properties are highly dependent on the temperature.

Even though many researches have been conducted on asphalt emulsion cold recycled mixtures [5,6] very few studies have been performed on cold recycled mixtures containing high Portland cement. Mixture evaluated in this study was design about 20 years ago in Korea as a cold central plant recycled asphalt mixture, to be used in the base layer. However, because of too high ratio of cement to emulsion, it became too brittle and more similar to cement treated RAP mixture. Unfortunately, it was observed that the pavement with this mixture ("Contractor mix") had cracks and other distresses on the surface (Fig. 1). Because of lack of researches and specifications about cold recycled asphalt mixtures at that time, it was not designed according to any confirmed procedure. That is why researchers in this study were suspicious about this material as a cold recycled asphalt mixture and tried to understand category and characteristics of this material via performing a literature review and experimental investigation. While initially this material was named cement treated cold recycled asphalt mixture, because of different nature of this mixture compared with cold mix asphalts, it will be called as “”Contractor mix” in the rest of this manuscript.

Because the studied material includes both asphalt emulsion and Portland cement it was a kind of new nature, so, not quite the same material could be found at the conducted literature reviews, however, the following studies were found to be the closest ones.

In an investigation conducted by Guthrie et al. [7] different combinations of RAP and cement contents were studied. It was reported that RAP contents between 50%–75%, and Portland cement content of 1.0% by the weight of RAP, can result a mixture with the best results compared with other mixtures with different combinations of RAP and cement contents. In another study performed on CIR mixtures containing RAP and cement [8], it was found that Portland cement could improve Marshall stability, resilient modulus, IDT strength, moisture sensitivity and rutting resistance of CIR mixtures. Yuan et al. [4] studied cement-treated RAP as base layer material. Effects of different parameters such as IDT strength, resilient modulus, cement content and RAP content were evaluated in a mix design. According to the tests results, it was found that there are direct relationships between contents of RAP and cement on one side, and mechanical characteristics such as strength and modulus on the other side. Those relationships were discussed and suggested for mix design consideration. Khay et al. [9] studied the formulation and mechanical characterization of cement-treated RAP material as a rehabilitated base layer material. It was concluded that higher RAP content leads to higher elastic modulus, compressive strength, IDT strength, and flexural strength. Asphalt Recycling & Reclaiming Association (ARRA) recommends a minimum 3:1 ratio of residual asphalt to cement in making cement treated cold recycled asphalt mixture. Also, according to ARRA recommendation, cements contents should be kept low, typically 0.25% to a maximum of 1.0% of RAP weight content, to prevent brittle behavior of the cement treated cold recycled mixture. The ratio of asphalt residue to cement should be a minimum of three to one [10], however, this ratio was one to four for the studied "Contractor mix". As a result, this ratio was 12 times lower than the minimum ratio

Fig. 1. Sample distresses of pavement constructed by "Contractor mix" ; a) Three years old pavement- Low traffic, b) Eight years old pavement- Low traffic, c) Six years old pavement- Medium traffic, d) Eight years old pavement- Medium traffic.

recommended by ARRA [10]. It showed this mixture could not be categorized as a cold recycled asphalt mixture, however, to better understand the mechanical characteristics (rutting and moisture susceptibility) as well as effects of containing asphalt emulsion and liquid polymer additives on the visco-elastic behavior of this material, this study was continued by conducting aforementioned experimental activities.

2. Statement and objectives

Rhode Island (RI) base layer HMA and a typical concrete were used as reference materials for comparative analysis. Laboratory experiments were divided into two parts, i.e., asphalt and concrete testing. To evaluate the visco-elastic characteristics of "Contractor mix", the following properties were first determined: Marshall stability and flow, Indirect Tensile (IDT) strength, moisture susceptibility using IDT and rutting resistance using Asphalt Pavement Analyzer (APA). On the other hand, to evaluate the elastic behavior of this mixture, compressive strength test was performed. A flowchart of the statement and objectives of this study are shown in Fig. 2. Also, cross sections of pavements made by Contractor mix as well as two reference mixtures (HMA and PCC) could be seen in Fig. 3.

3. Materials and test methods

3.1. Materials

3.1.1. Asphalt binder and aggregate

The aggregate gradation specification of RI base HMA was used for making HMA specimens. Asphalt binder used was PG 64-28. Portland cement concrete was in accordance with Rhode Island Department of Transportation (RIDOT) standard specification [11].

The mix design provided by KICT (Korea Institute of Construction Technology) was used to prepare "Contractor mix" specimens. The same material and ratios as "Contractor mix" base layer in Korea were used to make specimens in the asphalt

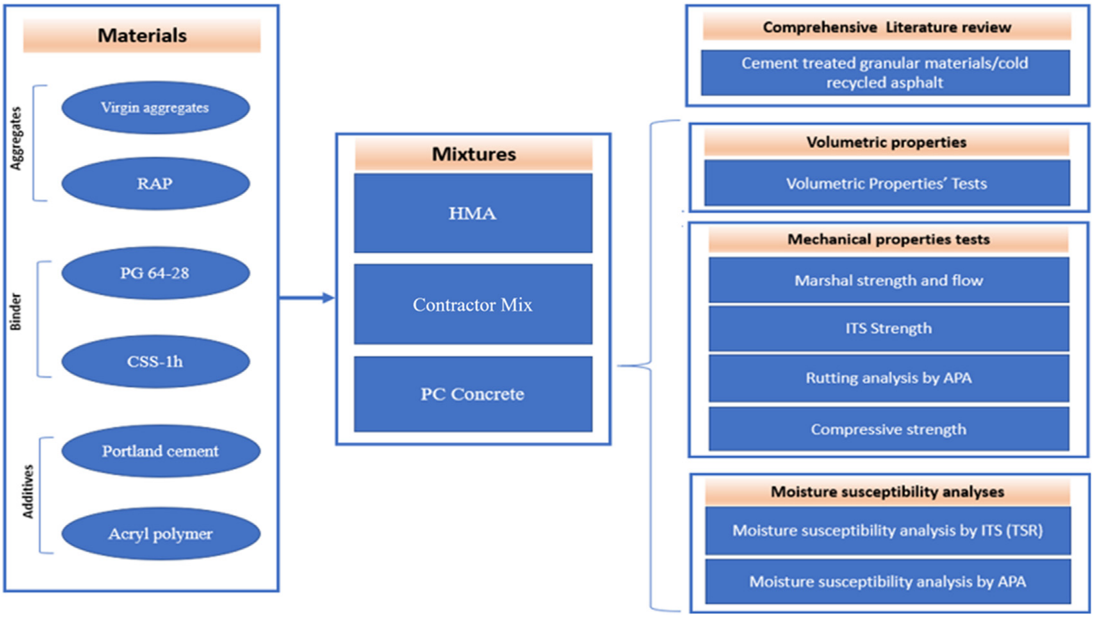

Fig. 2. Flowchart of statements and objectives of this study.

laboratory of the University of Rhode Island. Ratio of incorporated materials is shown in the Table 1. Also, gradation of RAP aggregates and total used aggregates (Rap and virgin aggregates) are shown in Tables 2 and 3, respectively.

3.2. Specimens preparation

Because "Contractor mix" layer of the studied pavement was not thick enough to prepare proper core for all conducted tests in this phase as well as next phase of this study, it was decided to make that mixture in the lab as similar as possible to the field mixture, using the same materials provided from Korea and using the same mix design and volumetric properties. A few cores were provided from the pavement in the Korea to determine the volumetric properties of the studied "Contractor mix".

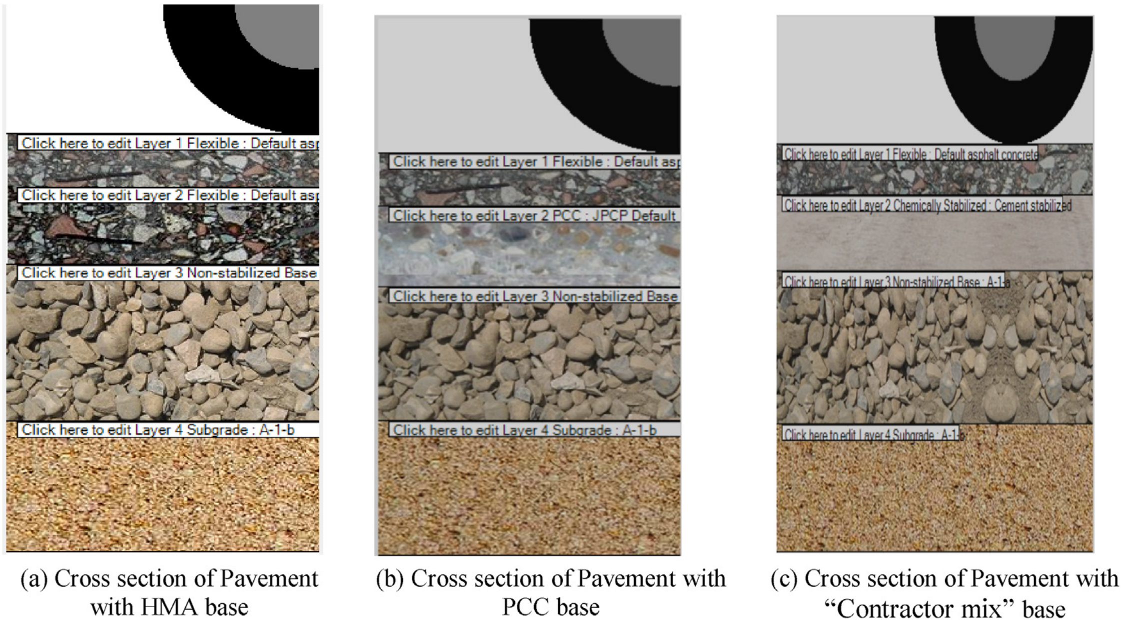

Fig. 3. Cross sections of modeled pavements.

Table 1
Composition of studied "Contractor mix".

Components	Components, Typ. (Range), %
−25 mm + 13 mm RAP	55
−13 mm RAP	25
−25 mm + 13 mm Virgin Aggregate	11
Portland Cement	4 (2 to 6)
Acryl Polymer	4 (3 to 10)
Asphalt Emulsion	1 (0.2 to 2.5)

Table 2
Gradation of used Rap aggregates.

Sieve Size	1 1/4"	3/4"	1/2"	3/8"	#8	#30	#50	#200	Tray
Passing (%)	100	91	61.8	46.8	15.9	5.1	2.6	0.5	0
Remained (%)	0	9	29.2	15	30.9	10.8	2.5	2.1	0.5

Table 3
Gradation of total used aggregates (Rap and virgin aggregates).

Sieve Size	1 1/4"	3/4"	1/2"	3/8"	#8	#30	#50	#200	Tray
Passing (%)	100	94.8	77.3	68.3	28.5	8.7	4.2	0.8	–
Remained (%)	0	5.2	17.5	9	39.8	19.8	4.5	3.4	0.8

Marshall mix design was carried out first, and the following procedure was applied for making HMA specimens. 1200 *g* of aggregates and asphalt binder were heated up to 175 °C. They were mixed and poured in a preheated mold to be compacted by 75 blows on each side, at 150 °C. After some trial and error, the amount of mix to achieve a thickness of 63.5 ± 3 mm was determined. Five different asphalt cement (AC) contents were varied by 0.5%, i.e., 4.0, 4.5, 5.0, 5.5 and 6.0%. As a result, Optimum Binder Content (OBC) for RI HMA was determined 5.1%. Regarding the "Contractor mix", water content of aggregates was found to be 1% and according to KICT instruction no more water should be added to this mixture. Observations of mixing process and performed proctor tests showed that adding 4% liquid polymer additive made the "Contractor mix" wet enough to be homogeneously mixed and compacted properly. In the other word, all aggregates were coated by asphalt emulsion and cement, also, the highest specific gravity was achieved when 4% liquid polymeric additive was added. Marshall compactor was used to make RI HMA and "Contractor mix" specimens for Marshall and IDT tests.

On the other hand, the SuperPave Gyratory Compactor (SGC) was employed to prepare HMA and "Contractor mix" specimens for moisture susceptibility and rutting tests by APA as well as making "Contractor mix" specimens for compressive strength test.

RI base aggregates batches weighing 11,400 *g* were prepared for making samples in 4%, 4.5%, 5% and 5.5% binder content by weight of total mixture. Every 11,400 *g* batch was used to make two specimens (9400 *g*) and 2000 *g* was used for determining maximum specific gravity, Gmm. Mixtures were placed in the oven for 4 h at 135 °C to age them. The SGC pressure was set to 87 psi, the angle of gyration to 1.25°, speed of gyration was standardized at 30 rpm and 205 gyrations were applied to every HMA specimen. OBC achieved by SuperPave mix design was 4.8% [12].

To make the PC concrete mixture, following the RIDOT standard specification [13] for concrete type xx, 415 kg/ m^3 (700 lbs/cy) and 0.42 were selected as cement factor and maximum water/ cementitious ratio, respectively. Concrete materials were mixed together during 5 min by a drum mixer. Prepared mixture was poured into cylindrical molds in three equal layers by tapping 25 times each layer by the standards tapping rod. Ten specimens of 100 mm (4 in.) diameter. by 200 mm (8 in.) height were prepared. 24 h later, concrete specimens demolded were submerged in a water tub. Every two specimens were tested for compressive strength at different periods (2, 7, 14, 21 and 28 days) to evaluate change of their compressive strength, according to AASHTO T 22 [11].

After making "Contractor mix" according to KICT instruction, it was evaluated to determine the best curing condition and time to prepare representative "Contractor mix" specimens. It was found that curing at 60 °C for two days following by 24 h at environment temperature produces the most appropriate specimens according to indirect tensile and compressive strength tests results. As a result, the following procedure was used to make "Contractor mix" specimens:

(1) Mixture of RAP + virgin aggregates + Portland cement in accordance with the ratio shown in Table 1 were dry mixed for 1 min at room temperature.
(2) After mixing, liquid additives and asphalt emulsions were then added to the mixture prepared under Step 1 above, and wet mixed at room temperature for 3–5 minutes.

(3) Marshall "Contractor mix" specimens were initially made by 75 impacts. However, Marshall "Contractor mix" specimens were compacted by 48 impacts on each side at 25 °C to achieve the same specific gravity as field "Contractor mix" cores. Specimens made by Marshall method were used for Marshall and IDT tests. The SGC specimens were prepared by 180 gyrations. The number of compactions was chosen again to achieve same bulk specific gravity as field "Contractor mix" cores. Specimens made by Superpave method were used in APA test.
(4) Compacted specimens were cured at 60 °C (or 140 °F) for Marshall or SGC molds for 48 h in the oven. Specimens remained in the molds with caps on both sides while they were curing in the oven.
(5) After curing process, specimens were cooled down in the mold to room temperature (about 2 h) and were taken out of the mold.
(6) After measuring height and weight of the cured specimens, their bulk specific gravity was determined.

Bulk specific gravity was used as a criterion to reach the same density and air void as field "Contractor mix" cores in this study. Following AASHTO standards for all conducted tests, three repetitions of each test for each material were made.

3.3. Indirect tensile strength and moisture sensitivity

Moisture susceptibility of the HMA and "Contractor mix" was evaluated by modified- Lottman or AASHTO T283 procedure [11]. All HMA specimens were compacted to reach of 7% ± 1.0 air voids. Dimensions of prepared specimens were 100 mm and 64 mm for diameter and height, respectively. HMA specimens were fabricated at Optimum Asphalt Content (OAC) and "Contractor mix" specimens were prepared according to the KICT procedure.

Six specimens were used: three for unconditioned and three for conditioned. Unconditioned specimens were tested without any treatment, while conditioned specimens were treated by moisture conditioning as follows:

- Specimens were saturated by submerging in water (up to 55–80% saturation level).
- Freeze at −18 °C for 16 h.
- Specimens were placed in a 60 °C water tub for 24 h.

Average tensile strength was determined for each of the unconditioned and conditioned specimens at 25 °C. Then, Tensile Strength Ratio (TSR) was calculated as a parameter which indicates moisture susceptibility of asphalt mixture [14].

3.4. Rutting and moisture susceptibility with asphalt pavement analyzer

Asphalt Paving Analyzer (APA) machine shown in Fig. 4, was used to evaluate resistance of HMA and "Contractor mix" e against moisture damage. This machine can measure rut depth created by repeated loads and has been accepted by many agencies to evaluate rutting resistance of mixtures prepared by SGC [15]. The used APA model (HM-459) complied with AASHTO standard T 234 Hamburg Test and AASHTO T 340 APA Rut Test. Test temperature is supposed to be set at the high temperature of the Performance Graded (PG) asphalt binder. Thus, 64 °C was selected as temperature for rutting test by APA. Rut depth was recorded automatically for 6 specimens after 8000 repetitions.

Fig. 4. Installed specimens on Asphalt Pavement Analyzer (APA) machine.

Another property of mixtures evaluated by APA was moisture susceptibility. Although the APA was programmed to apply 20,000 cycles in moisture susceptibility test, some of HMA samples failed before this number of cycles. To prevent failure of HMA samples as well as having a constant number of cycles for both rutting and moisture susceptibility tests, 8000 cycles was also chosen for moisture susceptibility test.

The procedure for conditioning selected specimens was similar to the method of AASHTO T283. However, vacuum saturation percentage was not targeted specifically, but vacuum was applied a given duration (6 min) and pressure (28 mm Hg). The resulting degree of void saturation from this procedure was generally between 55 to 80 percent. Immediately after determination of Saturated Surface Dry (SSD) weights, specimens were tightly wrapped with plastic wrap and placed in large freezer bags with 10 ml of water. To prepare conditioned specimens, they were kept at -18 °C for sixteen hours using a freezer, then placed in a 60 °C water tub for 24 h followed by a 25 °C water tub for two hours.

Finally, two specimens of each preconditioning specimens were evaluated by the APA. Four preconditioning specimens were made by the following procedures:

1 The first preconditioning was conducted by placing specimens in the APA machine at temperature of 58 °C for six hours before running test. Specimens treated by this condition procedure were referred as unconditioned-dry specimens.
2 The second preconditioning was conducted by submerging specimens in a 58 °C water tub for 2 h before running test. In this condition, specimens were tested by APA machine, while submerged in 58 °C water. Specimens treated by this condition were referred as unconditioned-wet specimens.
3 In the third preconditioning, specimens were conditioned in accordance with AASHTO T283 procedure [11], and they kept in the APA's water bath at 58 °C for two hours. Then APA test was conducted while specimens were submerged in 58 °C water. Specimens treated by this condition are referred as conditioned-wet specimens.
4 In the fourth preconditioning, specimens were conditioned just like method described in the third preconditioning above (applying freeze-thaw cycle of AASHTO T283). And, as in the unconditioned-dry state, specimens were placed in chamber temperature of 58 °C for six hours prior to running the APA. This condition is referred to as conditioned-dry.

Specimens were tested under all these four conditions to determine effects of different conditions on specimens' properties and results. Eventually to determine moisture susceptibility of samples, deformation of specimens in conditioned-wet (A) and unconditioned-dry (B) conditions were used shown in the following Eq. (1).

$$\text{Moisture Susceptibility Ratio} = A / B \tag{1}$$

Where:
A = Deformation of conditioned-wet mode
B = Deformation of unconditioned-dry mode

4. Results and discussion

4.1. Marshall Properties of "contractor mix"

Initially nine "Contractor mix" specimens were made by 75 Marshall hammer impacts on each side, and it gave specific gravity of 2.17. Since specific gravity of field cores was 2.08, it was necessary to reduce compaction effort to have comparable bulk specific gravity and consequently air voids. By trial and error method, it was found that 48 Marshall hammer impacts on each side of specimen led to specific gravity of 2.08. Then, another nine "Contractor mix" specimens were made by 48 compaction blows. Table 4 shows the comparison between RI HMA and "Contractor mix" specimens. It was observed that "Contractor mix" specimens made by any compaction effort had higher stability compared with HMA specimens. On the other hand, they had lower flow and bulk specific gravity in comparison with HMA. Having high stability and lower flow shows that "Contractor mix" is stiffer than HMA. Lower bulk specific gravity demonstrates less density of "Contractor mix" in comparison with RI HMA. Typically, density and stability have direct relationships, i.e., denser specimens have higher stability. In the present study "Contractor mix" had low bulk specific gravity and provided high Marshall stability. It could be attributed to the different rigidity of "Contractor mix" and HMA. "Contractor mix"' s binder is composite of asphalt and cement, so it is more rigid than HMA's binder, particularly at high temperatures like temperature of the Marshall test (60 °C).

Table 4
Comparison of Marshal properties for RI HMA and "Contractor mix".

Marshall Properties	RIHMA (At OBC)	Contractor mix (75 impacts)	Contractor mix (48 impacts)
Stability, N	14,679	26,044	15,253
Min Stability N (Medium Traffic)	3336	–	–
Flow, 0.01 in	15	5	5
Allowed Flow Range (Medium Traffic)	8-18		
G_{mb}	2.33	2.17	2.08

Generally, because of low percentage of asphalt emulsion (1%) and relatively high percentage of cement (4%), it seems that "Contractor mix" tends to behave more like a elastic material (such as concrete) than a visco-elastic material (such as HMA).

4.2. Results of indirect tensile (IDT) strength test

When comparing the average conditioned and unconditioned IDT strengths of "Contractor mix" and RI HMA in Table 5, it could be observed that "Contractor mix" has higher tensile strengths at both conditions. Such higher values could be attributed to the higher stiffness of "Contractor mix" in comparison with HMA. These results were compatible with the Marshall stability and flow results examined in previous section. TSR value, which is a parameter for evaluation of moisture sensitivity, is higher for RI HMA compared to "Contractor mix". However, TSR value is higher than the minimum amount according to AASHTO T283 criteria which is 80% for both mixtures [11]. Difference in moisture sensitivity of these two mixtures may be due to difference in aggregates gradation, aggregates quality, air voids as well as binder type.

4.3. APA test results

4.3.1. Results of moisture susceptibility test

Rutting depths after 8000 cycles are shown in Table 6, and HMA has experienced higher deformation than "Contractor mix". Ratio of deformation for condition and unconditioned specimens is a parameter that could be used as criteria to evaluate moisture susceptibility of mixture, similar to TSR in IDT test. However, it may be noted that ratio of APA results would be reverse to TSR value.

As shown in the Table 6 the ratio is almost the same in dry and wet conditions (113% and 111%, respectively) for HMA, while it has changed for "Contractor mix" from 111% to 145% when the condition changes from dry to wet. Ratio of "conditioned-wet specimens" over "unconditioned- dry specimens" was considered to determine moisture susceptibility of HMA and "Contractor mix" es by APA method. This combination of conditions combines the expected worst-case test scenario of preconditioning of samples and testing them while submerged. The deformation of samples tested with this most severe combination is divided by the results of unconditioned specimens tested in a dry state and the ratio is called "Critical (Conditioned/Unconditioned) Deformation Ratio (%)". Mixtures with potential moisture susceptibility would be expected to have a high ratio; whereas mixtures with low propensity to stripping would be expected to have a ratio near 100% [16]. Critical (Conditioned / Unconditioned) Deformation Ratio (%) of HMA and "Contractor mix" could be found at Table 6. It may be noted that "Contractor mix" was more susceptible to moisture damage compared with RI HMA. This result is compatible with results of TSR values.

Generally, TSR and APA deformation ratios show sensitivity of mixture to humid condition and/or freeze-thaw cycles. Nevertheless, it should be considered that if a mixture is more sensitive against moisture, it is not essentially weaker in this condition. For example, "Contractor mix" showed less TSR value and higher APA ratio in comparison with HMA. As a result,

Table 5
Comparison of IDT Test Results for RI HMA and "Contractor mix".

Items	RI HMA	"Contractor mix"
Unconditioned IDT Strength, psi	131.5	165.7
Conditioned IDT Strength, psi	116.7	134.8
TSR	0.89	0.81
TSR Criteria	Min 0.80	Min 0.80
TSR Result	pass	pass

Table 6
Deformation (mm) @8000 cycles and 58 °C.

Mix	Load Type	Specimen Type	Pre-Condition	Test Condition	Deformation (mm)	Conditioned / Unconditioned Ratio (%)	Critical Conditioned/ Unconditioned Ratio
HMA	Hose	Cylinder	No	Dry	8.10*	113	109
HMA	Hose	Cylinder	Yes	Dry	9.15		
HMA	Hose	Cylinder	No	Wet	7.95	111	
HMA	Hose	Cylinder	Yes	Wet	8.85*		
Contractor	Hose	Cylinder	No	Dry	3.60**	111	161
Contractor	Hose	Cylinder	Yes	Dry	4.00		
Contractor	Hose	Cylinder	No	Wet	4.10	141	
Contractor	Hose	Cylinder	Yes	Wet	5.80**		

* Values used to calculate Critical Moisture Susceptibility Ratio of HMA.
** Values used to calculate Critical Moisture Susceptibility Ratio of "Contractor mix".

both of those tests indicate that “Contractor mix” is more sensitive to moisture compared with HMA. Nevertheless, “Contractor mix” had higher IDT strength and less deformation than HMA at IDT and APA tests, respectively. Therefore, “Contractor mix” is more sensitive than HMA to moisture, but it is still stronger than HMA in this condition.

4.3.2. Results of rutting test

Results of rutting test are highly influenced by HMA mechanical properties, temperature, hose characteristics and applied pressure. Rutting of HMA in APA test is usually between 5–20 mm after 8000 times repetitions. Rut depth of all HMA specimens was in this range and “Contractor mix” specimens were less than 5 mm. As shown in Table 7 the average rut depths of HMA and “Contractor mix” with 8000 cycles of 120 psi hose pressure were 10.8 mm and 4.7 mm, respectively. Therefore, HMA experienced 5–6 times more permanent deformation (rut depth) than “Contractor mix” as it was expected. Such a difference in rutting could be attributed to the difference in physical properties of aggregates and binders. Although HMA specimens were made by virgin aggregates, its binder was neat asphalt which is a visco-elastic material. So, by increasing temperature viscosity of asphalt changes and mixture becomes softer than the one at lower temperature. On the other hand, “Contractor mix” is made by weaker aggregates (RAP) and its binder is composite of cement and asphalt emulsion. RAP aggregates have weaker strength against applied stress by hose, and they tend to be crushed or deformed easier than virgin aggregates of HMA specimen. On the other hand, binder of studied “Contractor mix” that is mix of a elastic material (cement) and a visco-elastic material (asphalt) is less dependent on the change of temperature.

4.3.3. Material categorization of the studied mixture

Since studied “Contractor mix” is a material which contains both cement and asphalt binder, the question remains, should it be categorized as a quasi-elastic material like concrete or visco-elastic material like asphalt mixture. To be able to answer this question correctly, it was essential to apply the same test on all three “Contractor mix”, HMA and concrete.

Mechanical properties of visco-elastic materials e.g., asphalt mixture are highly dependent on temperature. On the other hand, mechanical properties of quasi-elastic materials e.g., Portland cement concrete are much less dependent on the changes of temperature. To determine whether “Contractor mix” behaves like visco-elastic or quasi-elastic material, rutting test was performed by APA. This test was conducted on all three of HMA, “Contractor mix”, and PCC at three different temperatures of 25, 45 and 64 °C.

As can be seen in Fig. 5, rutting depths of “Contractor mix” and PCC at 25 °C are almost similar and less than 1 mm, while HMA showed rut depth nearer to 3 mm. Such a difference in results between HMA and other two mixtures could be attributed to the difference in stiffness between HMA and other two materials. As could be comprehended from Marshall flow results, “Contractor mix” is stiffer than HMA.

Table 7
Average rut depth of HMA and “Contractor mix” @ 64 °C.

Mix	HMA	Contractor mix
Rut depth (mm)	10.80	4.70

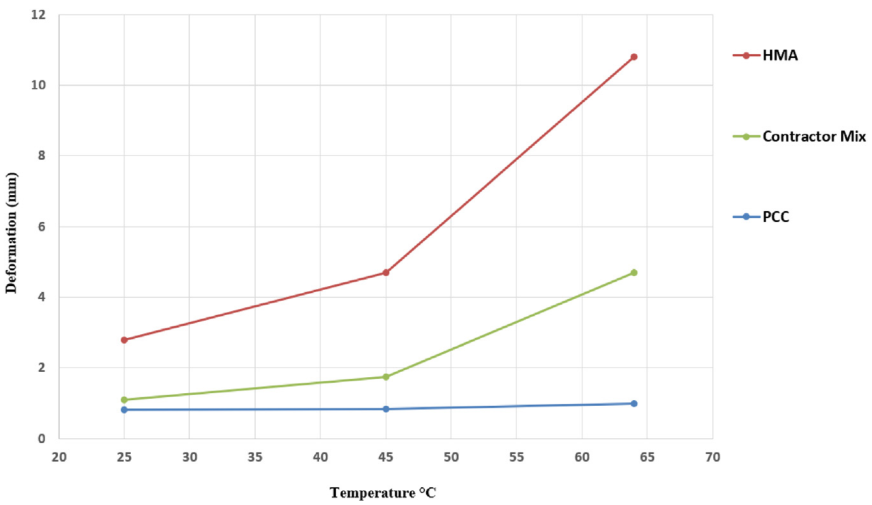

Fig. 5. Rut depth of “Contractor mix” Mixture, HMA and PCC @ 25, 45 and 64 °C.

By increase of temperature, rut depth of HMA and “Contractor mix” increased, while it almost remained constant for concrete (negligibly increased). This increase means “Contractor mix” and HMA has become softer in higher temperature and their properties are dependent on the changes of temperature unlike concrete, although this dependency is more severe for HMA in comparison with “Contractor mix”. Since there is no limitation to distinguish an elastic material from a visco-elastic one it is hard to tag studied “Contractor mix” as one of these two, however, considering deformation diagrams shown in Fig. 5, properties of “Contractor mix” were more similar to PCC at low temperature while it behaved something between HMA and PCC at high temperatures. The average highest temperature of Seoul as a representative city for South Korea is 30 °C [17]. Thus, it could be concluded that “Contractor mix” behaves similar to a quasi-elastic material rather than visco-elastic in such condition. According to AASHTO standard for cement treated aggregate base (AASHTO SC-M-308) the Portland cement added to the aggregates is typically between 2.5% to 5% by weight of aggregates. In the studied “Contractor mix”, Portland cement content was 4% by the weight of mixture that places PC% in the determined range by AASHTO for cement treated material, however, the studied “Contractor mix” includes 1% asphalt emulsion and 87% of aggregates are replaced by RAP material. The studied “Contractor mix” is different from cement treated granular material because of containing asphalt emulsion and RAP, on the other hand, it is different from cold central plant recycled asphalt mixture because of high content of Portland cement, however, these two material categories are closet categories to the studied mixture. Finally, considering results of conducted tests, high stiffness of cement treated mixture and performed literature reviews, it was recognized as a kind of cement treated granular material.

4.4. Results of concrete tests

Results of compressive strength test are shown in Fig. 6, and it could be observed that there is a considerable and meaningful gap between PCC and “Contractor mix” specimens. Therefore, PCC specimens are much more resistant against compression in comparison with “Contractor mix”. It may be attributed to the higher quality of virgin aggregates, better gradation of aggregates as well as higher quality of binder in concrete compared with “Contractor mix”. As can be seen in Fig. 6, compressive strength of concrete is 5–6 times higher than “Contractor mix” at the same curing times. Binder of “Contractor mix”, which is contained of asphalt emulsion and cement, may not be as homogenous and strong as cement in PCC. Asphalt emulsion and cement are two materials with different natures and properties. The bond between molecules of these two different materials might not be compatible and not as strong as bonds between cement molecules. Consequently, such weaknesses may lead to much less compressive strength of “Contractor mix” in comparison with PCC. Shown in the Table 8, it was also found that compressive strength of PCC specimens (5508 psi) were higher than the minimum value according to standard specification of RIDOT [13], that is 4000 psi after 28 days for concrete base layer (Concrete type XX). Thus, tested PCC is qualified to be used in base layer. On the other hand, “Contractor mix” compressive strength was found to be 960 psi that is less than the minimum strength for concrete base layer and might not be strong enough to be used as a concrete base layer material. In conclusion, although “Contractor mix”’ s rigidity is closer to concrete rather than HMA, it may not be strong enough as concrete base layer material too.

Regarding the reflective and transverse cracking problem of CTR material in Korea, these distresses are usually attributed to compressive strength and flexural strength for Portland cement concrete as well as cement treated martials, specifically in pavement [18]. That is why it was tried to have an understanding about this characteristic of studied PC concrete and CTR material. However, the best correlation for specific materials is obtained by laboratory tests for given materials and mix design, because of laboratorial limitations it was tried to reach an understanding of flexural strength for studied materials by proposed empirical equations. Totally, flexural strength is about 10–20 percent of compressive strength depending on the type, size and volume of coarse aggregate used [19]. Eq. (1) shows an empirical relationship between flexural strength and compressive strength of Portland cement concrete proposed by ACI [20]. According to this equation there is a direct

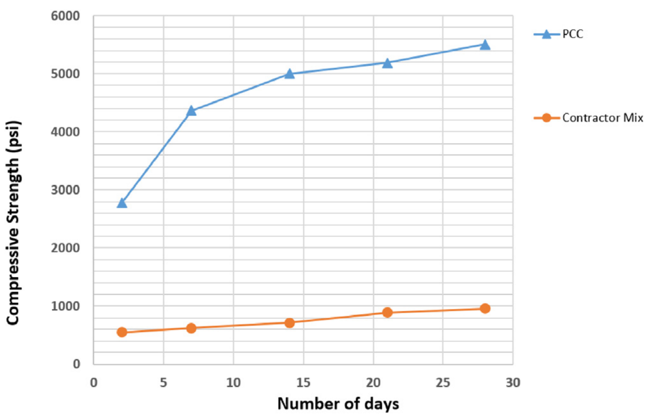

Fig. 6. Compressive Strength of “Contractor mix” Mixture and PCC Cylindrical Specimens.

Table 8
Compressive strength test results.

Properties	Unit	Contractor mix	PCC
Compressive Strength (28 days)	psi	960	5,508

relationship between compressive strength and flexural strength. Since studied CTR material had considerably lower compressive strength (5–6 times) than concrete, by some approximation it could be concluded that it has lower flexural strength, too.

$$f_r = 0.62\sqrt{f_c'} \quad (2)$$

where f_r = modulus of rupture (flexural strength) at 28 days in N/ mm2 and f_c' = cylinder compressive strength at 28 days in N/mm2.

5. Conclusions and recommendations

5.1. Conclusions

As a comprehensive investigation was conducted on "Contractor mix" modified with high cement content. In the first phase of this study, some mechanical properties and moisture susceptibility of this mixture were evaluated and compared with conventional HMA and PC concrete. Performed evaluations showed that studied "Contractor mix" behaves more like PC concrete rather than asphalt mixture. In addition:

- Performed literature review showed that ARRA recommends a minimum 3:1 ratio of residual asphalt to cement for emulsified asphalts to prevent brittle behavior of mixture, however, this ratio was 1–4 for the studied "Contractor mix" (12 times less than minimum ratio).
- It was observed that some of RAP aggregates were crushed when they were being compacted by Marshall Hammer. It can affect grading of aggregates in "Contractor mix" specimens and consequently may not represent materials in the field. On the other, SGC could better lead to specimens representing "Contractor mix" in the field. Also, It was found that "Contractor mix" specimens had higher Marshall Stability, less flow and less density in comparison with HMA.
- Comparing conditioned and unconditioned IDT strengths of "Contractor mix" and RI HMA showed "Contractor mix" had a higher tensile strength at both conditions. Also TSR values are higher for RI HMA compared with "Contractor mix", however both TSR values are higher than the minimum recommended by AASHTO T283, i.e., 80%.
- APA test showed that "Contractor mix" was more sensitive to moisture damage compared with RI HMA. This result was compatible with the one by TSR. Also HMA experienced 5–6 times more permanent deformation (rut depth) than "Contractor mix" by APA.
- Compressive strength of "Contractor mix" was observed to be 5–6 times less than PC concrete. Transverse and reflective cracking of pavements made by PC concrete or PC treated base layer are highly related to compressive and flexural strength of those materials, so, cracking happened in roads of Korea constructed with the studied "Contractor mix" material could be attributed to this factor. Another reason could be shrinkage cracking. Because of relatively high cement content of "Contractor mix", it is prone to shrinkage, on the other hand low compressive and flexural strength of this cementitious material make it more vulnerable against shrinkage.
- Generally, it seemed that "Contractor mix" behaved like a semi rigid material, or more like a rigid material than a flexible one. That is why, this mixture will be more evaluated as well as modeled as a rigid and cementitious material in the second phase of study, not as an asphalt mixture. On the other hand, proper mix-design to make this mixture to a cold recycled asphalt mixture will be found, too. All, old "Contractor mix", new designed cold recycled asphalt mixtures, HMA and PCC mixtures will be modeled by the Pavement ME software to predict and compare their performance during the design life time.

5.2. Recommendations

- In the next phase of study cold recycled asphalt mixtures treated with Portland cement will be designed according to the ARRA standard recommendations and using the same materials as Korean "Contractor mix".
- Other mechanical properties of studied "Contractor mix", new cold recycled asphalt mixtures (made by the same Korean materials as studied "Contractor mix") and Rhode Island base materials (HMA and PCC) will be evaluated in the second phase. Then, experimental data will be used as material input data in AASHTOWare ME Design software to model pavement constructed by those four different materials. The software will predict Distresses for different pavement types and results will be compared between them.

Conflict of interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript

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