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USE OF MARBLE WASTE AS A ROAD BASE MATERIAL IN DIFFERENT SIZE RANGES

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Abstract. Along with the economic loss caused by the non-use of waste worldwide, uncontrolled storage also brings an additional cost. Today, the rapid increase in the population and the rapid depletion of natural resources in nature lead us to research the recycling possibilities of waste materials. In this context, using marble waste in road pavements is one of the best areas of use. This study investigated the suitability of substituting the marble waste obtained from a marble quarry in Bilecik, Turkey, in the road base layer instead of the aggregate, which was used all the time in the base layer in highway construction at different intervals. The physical tests carried out in this context have met the base material limit conditions of the Turkish Highways Technical Specification (THTS). Mixtures obtained in modified Proctor experiments, and optimum water contents (w_{opt}) and maximum dry unit volume weight (rdmax) were determined for each mixture. California bearing ratio (CBR) values remained above the limit value of all mixtures for 0 days and 7 days of curing according to the specifications for THTS. In addition, CBR values were obtained after freezing-thawing at 4, 12, and 20 cycle numbers. According to the freeze-thaw test results, there was an increase in CBR values in the first 4 cycles and a decrease in the following cycles. Still, all the test results obtained remained

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above the limit value according to the specifications for THTS. Aggregate unit cost constitutes approximately twice the unit cost of marble waste. Besides, this difference has created an economic equality distance of 18.9 km. Therefore, a marble quarry, a road construction site within the calculated economic equality distance and marble waste material will provide a financial gain for our country. With the evaluation of quarry waste all over the world, we can leave a liveable world with rich raw material resources and a strong economy for future generations.

Keywords: California bearing ratio test, marble waste, road base material, waste management.

Introduction

As a result of technological developments and the continuous increase in the world population, waste is formed. The rapid increase in industrial waste volume causes environmental pollution, which adversely affects natural life. With the rapid depletion of natural resources globally, solving these problems is also of great importance. Consequently, various studies are conducted on waste management issues such as reducing waste generated, utilizing existing waste as a source of raw material, and recycling used natural materials. Especially the production amount reaches millions with its reuse as a raw material resource in different industries; recycling becomes important due to cost reduction, waste disposal, and efficient resource use. Environmental and other aspects of marble waste can be a list; waste is indestructible, the areas where the waste can be dumped are limited, and its appearance is ugly, they pollute the soil in the area where it is poured, it pollutes the water resources in the area where it is poured and, it pollutes the air (Kushwah et al., 2015). Figure 1(a) shows the situations and destructions created by marble quarries in nature. Considering that the waste material is removed from the quarry site for recycling, the image that

Figure 1. a) uncontrolled waste storage; b) controlled waste disposal (modelling)

will emerge in the quarry is modelled in Figure 1(b). As can be seen, adverse environmental factors may be prevented with waste control.

Aggregates are the most consumed material in the construction sector. Approximately 95% of the materials used in the superstructure in road constructions constitute an important area of this sector. The aggregate used in manufacturing is supplied from suitable aggregate quarries in the vicinity. Therefore, with the increasing need for aggregate, new aggregate quarries are increasing daily. As there is the increased need for aggregate quarries, deterioration occurs in the earth's general structure. Besides, with the decrease of quality materials in the quarries near the settlements, there is a tendency for the quarries to be located at a greater distance. As a result of this trend, there is an increase in transportation costs for the material supply (Yılmaz & Sütaş, 2008). For this reason, using waste in road construction provides multiple benefits. The need for raw materials in limited quantities in our nature has been reduced with waste recycling. Again, an economic benefit has been obtained (Dhanapandian & Gnanavel, 2009a; Dhanapandian et al., 2009).

In recent years, due to the high cost of road construction and the contribution they provide to the performance characteristics of the road superstructure where waste materials are used, researchers have turned to studies on the reuse of these waste materials (Drew et al., 2002; de Rezende & de Carvalho, 2003; Ahmed et al., 2014; Soleimanbeigi et al., 2015; Kawabata et al., 2016; Domitrovic et al., 2016; Ural & Yakşe, 2015; Mostafa, 2016; Forteza et al., 2004; Hjelmar et al., 2007; Xie et al., 2017; Nataatmadja & Tan, 2001; Camargo et al., 2009; Bejarano et al., 2003; Burreglo et al. 2009). Drew et al. (2002) compared the benefits created by using natural aggregate resources for humanity and the environmental impact of obtaining aggregate. Consequently, they said that using recycled aggregate in buildings, roads, and asphalt pavements would decrease the demand for new natural aggregate in the future. De Rezende & de Carvalho (2003) investigated the quarry waste of the Pedreira Contagem Area in the foundation layers of flexible road superstructures. As a result of the study, it was seen that the Pedreira Contagem Area quarry waste had potential use properties in the base layers of flexible pavements, which prospered the use as a base material on roads with low traffic density. Ahmed et al. (2014) studied the possibilities of using three different waste types, including marble waste, in the foundation layer and sub-base in road construction. The study handled ground phosphate, marble, and granite aggregates. Experiments were carried out to determine material physical, mechanical and chemical properties. Experimental results showed that all three waste materials discussed in the study could be used safely instead of aggregate in local low-volume road construction. Kailash et al. (2013) studied limestone waste characterisation as flexible pavement construction. The study included determining total limestone waste at the quarry sites in seven villages of Chittapurtaluk in Gulbarga district and experimental analysis of the collected limestone waste to specify their possible usage in flexible construction pavement layers. The laboratory results were compared with the results of basalt aggregates and it was observed that the CBR values of limestone waste were low compared to basalt. Still, they are relatively high if the usage in heavy traffic pavement construction is considered. The results also showed that the limestone waste had good interlocking properties compared to the basalt aggregates and therefore had outstanding dispersion characteristics for base and sub-base courses. They stated that limestone waste was economical compared to basalt as it only had transportation and processing expenses.

Kawabata et al. (2016) studied the effects of freeze-thaw history on granular base course materials' bearing capacity. The results showed that the CBR values for all the C-40-based specimens decreased when the material was subjected to freeze-thaw cycles for all water conditions. Consequently, they observed that CBR values decreased even for low water content due to a reduction in interparticle friction caused by the reduced interparticle surface moisture with freezing effects. Domitrovic et al. (2016) investigated the effects of moisture content and freeze-thaw cycles on the bearing capacity of reclaimed asphalt pavement (RAP) and natural aggregate mixtures. Three samples with uncuring and different curing conditions were prepared and tested. Another sample was tested after soaking in water for 96 hours. The last sample was tested after it was subjected to 14 freeze-thaw cycles. The results showed that RAP and crushed limestone mixtures were less sensitive to moisture content, and an increase in RAP content caused an increase in the sensitivity of mixtures to the moisture content. In their experimental study, Ural & Yakşe (2015) investigated marble waste as a road base material. In this context, resistance tests against weathering and freezing, Los Angeles test, flatness index test, organic matter determination test with NaOH, water absorption test, Atterberg consistency limit test, and methylene blue tests were performed on samples taken from three different regions. As a result of the experiments, the researchers stated that the physical and mechanical properties of marble waste met Turkish standards and that the waste could be used as a base/sub-base material. Mostafa (2016) conducted an experimental study to evaluate the use of some waste, including marble and marble dust, on different road layers. The use of marble and other waste types in the bottom base and foundation layer was evaluated. The researcher showed that the waste, including marble, could be used both in the sub-base and the foundation layer. In this case, savings in total costs were also possible. This study investigated the suitability of substituting the marble waste obtained from a marble quarry in Bilecik, Turkey, in the road base layer instead of the aggregate, which was used all the time in the base layer in highway construction at different intervals. In this context, it was examined whether the physical and mechanical experiments comply with the standards. Mixtures obtained modified Proctor experiments, and optimum water contents (w_{opt}) and maximum dry unit volume weight (rdmax) were determined for each mixture. CBR tests were conducted on mixtures for 0 days and 7 days, curing after 4, 12, and 20 cycles of freeze-thaw.

1. Material and method

1.1. Preparation of materials

Two materials, aggregate and marble waste, were used to prepare test samples in this study, which was carried out to evaluate marble waste in road construction. Road foundation material approved by the 14th Regional Directorate of Aggregate Highways (proper for THTS) was obtained from the quarry as aggregate (limestone type crushed stone). As seen in Figure 2, the material is broken with the help of a crusher and stocked in the furnace in dimensions of 0–5 mm, 5–12 mm, 12–19 mm, and 19–38 mm. The material used in the experiments was taken from the stock by appropriate sampling methods and taken to the laboratory environment.

Figure 2. Aggregate stock area

The material used as marble waste was obtained from a marble quarry in Bilecik province, Yenipazar district. Marble reserves in Bilecik province are concentrated along a line formed by the Central District, Gölpazarı District, and Yenipazar Districts. By taking samples from the Yenipazar district's marble waste within this line (Figure 3), the base material replaced the road superstructure. The experiments specified in the THTS were evaluated for their usability. In the industrial and commercial sense, the definition of marble has a very wide meaning. It is named metamorphic rock formed by the recrystallization of marble, limestone, and dolomitic limestone under the effects of pressure and heat.

All kinds of rocks that can give blocks can be polished by cutting and polishing, have the strength and look pleasing to the eye are defined as marble (Görgülü, 1994). In this study, marble waste taken from the marble quarry as rubble with an average diameter of 75 mm to 150 mm was crushed with a mini crusher in the laboratory, and samples in the range of 0–38 mm were obtained. This sample was sieved in suitable sieve intervals and classified in aggregate sizes taken from the quarry (Figure 3). Figure 4 shows the flow chart of the preparation of mixes and tests in this study.

X-ray diffraction (XRD), X-ray fluorescence (XRF), and scanning electron microscopy (SEM) analyses were made on the aggregate and marble waste used in the experiments. In this study, XRD analyses were performed on the aggregate of the İncirli quarry and the marble waste obtained from the Yenipazar district marble quarry Panalytıcal-Empyrean branded device. The mineral phases in the marble were

Figure 3. a) marble quarry supply of marble waste; b) material crushing with the help of mini crusher

determined with the help of X-ray diffraction graphs obtained. The graphics formed from this analysis are given in Figure 5. The aggregate and marble waste mineral phases were determined with the XRD graphics obtained due to XRD analysis. Calcium carbonate was the main mineral by XRD analysis on the İncirli stone quarry aggregate. Calcite was the main mineral in the marble waste fragments of the Yenipazar district of Bilecik (Turkey). The XRF analysis aims to determine the material content by semi-quantitative analysis. XRF analysis allows for semi-quantitative analysis of elemental content in percentage (%) and parts per million (ppm) in samples in different forms such as solid (mineral, rock, metal, soil), liquid (oil, water, petroleum products), and pressed powder. In this study, XRF analysis of the aggregate and the marble waste was performed with the help of a Panalytıcal-Axıos branded device. The values obtained as a result of the analysis are given in Table 1. As a result of the XRF analysis performed on aggregate

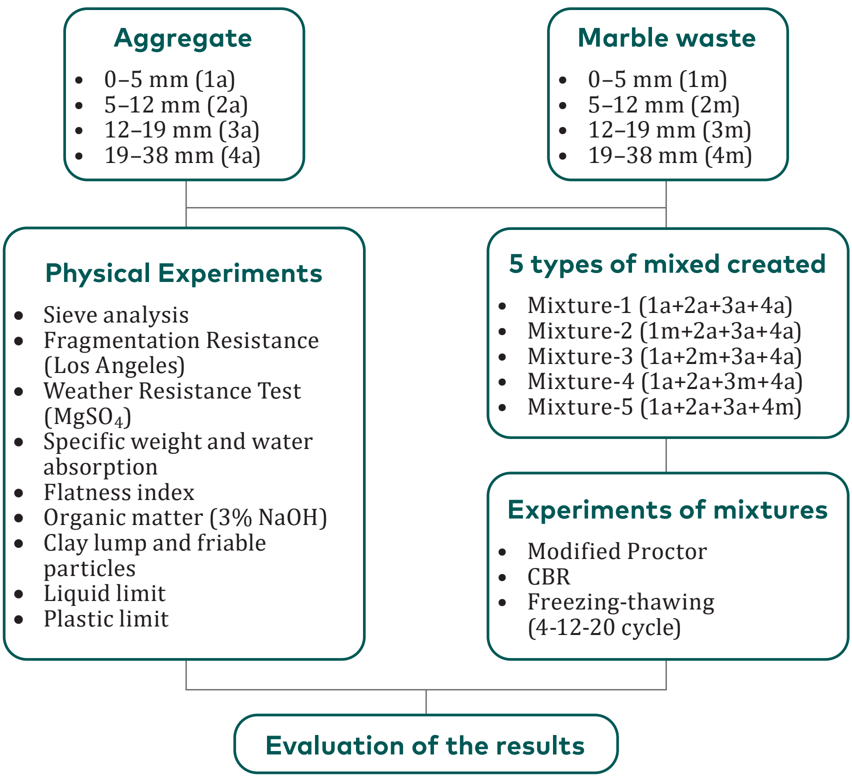


Figure 4. The flow chart of preparation of mixes and tests done

and marble waste, calcium (Ca) was the main element. Within SEM studies, observations were made to identify the samples' components, their mineral relations, morphological properties, and interpretations regarding the formation species and origin. Besides, semi-quantitative EDS (energy dispersive x-ray spectroscopy) can be performed in a chemical analysis at the required points. SEM analyses were performed on aggregate, and marble waste using a Zeiss-Supra 40Vp branded device. Images of the observations made are given in Figure 6. Besides, semi-quantitative EDS chemical analyses were taken from the required areas or points (Figure 7). Aggregate and marble waste EDS results prove the XRF analysis results, and it has been observed that the main element is calcium.

Mixtures were prepared according to the mixing ratios of the designed TYPE-1 PM base layer (Table 2) using different ranges of aggregates and marble waste (Figure 8). Details of the five mixtures obtained are given in Table 3 (Figure 9). All materials included in the mixture in Mix-1 shown in Table 3 consist of aggregate obtained from the quarries used in road construction under normal conditions. In Mix-2, the material between 0–5 mm is marble waste. Other intervals are aggregate. In Mix-3, the intervals outside the 5–12 mm interval are aggregate, 5–12 mm interval is marble waste, and in Mix–4 the range of 12–19 mm represents marble waste and other ranges – aggregate. Finally, in Mix-5, a 19–38 mm interval was prepared as marble waste.

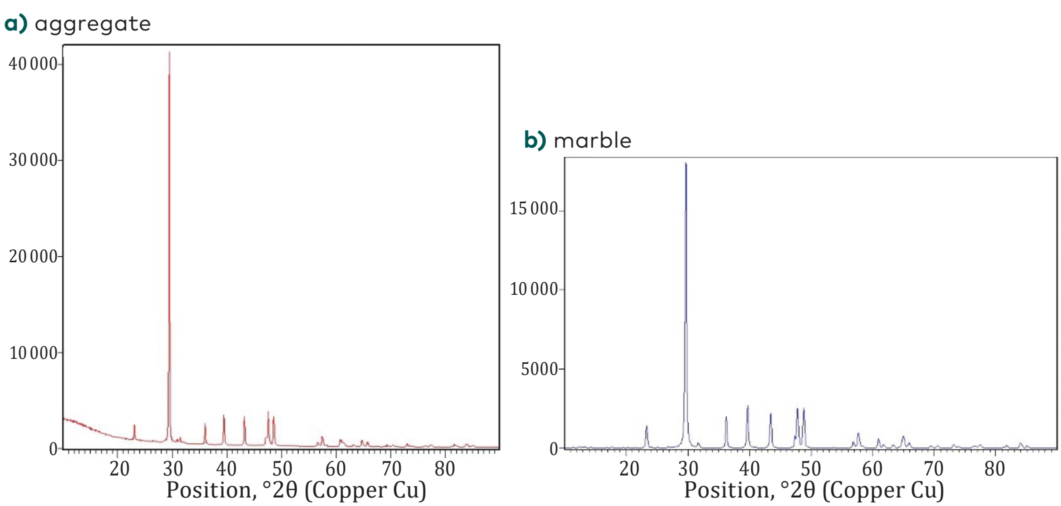


Figure 5. XRD analysis results of materials: a) aggregate; b) marble

Table 1. XRF analysis results

Component	Aggregate sample	Marble waste sample
O	0.889	–
Na	–	0.046
Mg	0.008	0.102
Al	0.007	0.115
Si	0.010	0.288
P	0.016	0.271
S	–	0.008
Cl	–	0.01
K	0.006	0.058
Ca	43.868	98.735
Ti	0.005	–
Mn	–	0.34
Fe	0.059	0.167
Ni	–	0.016
Zn	0.033	0.012
Sr	0.049	0.133
Pb	0.015	–

Table 2. TYPE-1 PM base layer mixture ratios

Sieve openings		Mixture % 100	THTS Part 402 PMT TYPE-1		Design tolerance limit	
inch	mm					
1–1/2"	37.5	100	100		100	
1"	25.4	86	72	100	79	93
3/4"	19	75	60	92	68	82
3/8"	9.5	57	40	75	50	64
No 4	4.75	45	30	60	38	52
No 10	2.00	31	20	45	26	36
No 40	0.425	15	8	25	10	20
No 200	0.075	6	0	10	4	8

Table 3. Mixture types

Mixture No	0–5 mm	5–12 mm	12–19 mm	19–38 mm
Mixture-1	Aggregate	Aggregate	Aggregate	Aggregate
Mixture-2	Waste	Aggregate	Aggregate	Aggregate
Mixture-3	Aggregate	Waste	Aggregate	Aggregate
Mixture-4	Aggregate	Aggregate	Waste	Aggregate
Mixture-5	Aggregate	Aggregate	Aggregate	Waste

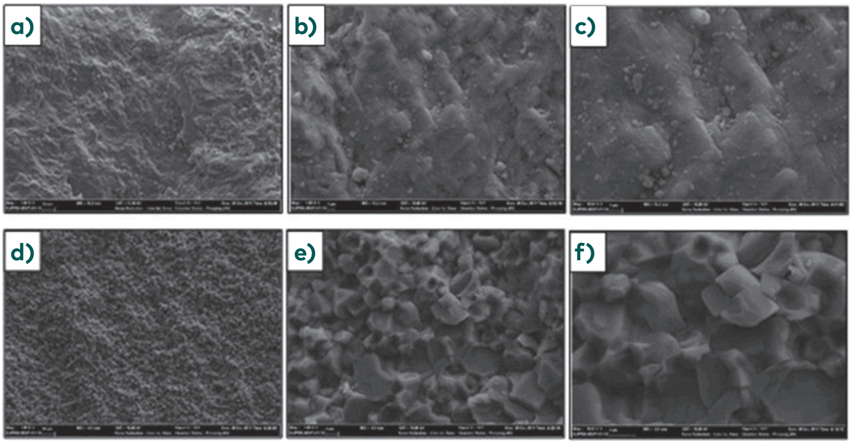
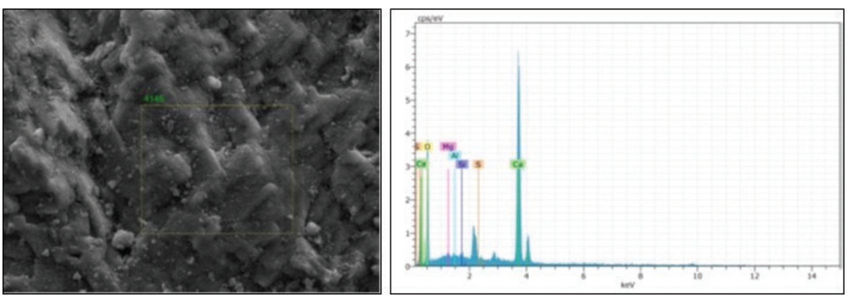


Figure 6. SEM images of materials: a) aggregate SEM image magnification × 1000; b) aggregate SEM image magnification × 5000; c) aggregate SEM image magnification × 10000; d) marble waste magnification × 1000; e) marble waste magnification × 5000; f) marble waste magnification ×10000

a) aggregate



b) marble waste

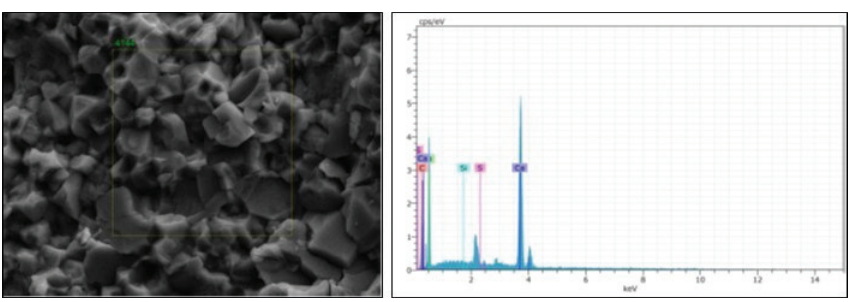


Figure 7. EDS image and graphic of materials: a) aggregate; b) marble waste

Figure 8. Aggregate and marble waste samples

Figure 9. Photographs of prepared five mixtures

1.2. Physical tests

Sieve analysis test, determination of fragmentation resistance (Los Angeles abrasion test), frost resistance test with $MgSO_4$ in coarse aggregates, specific gravity, water absorption test, flatness index test for granular base material according to THTS were taken. Liquid limit, plastic limit, organic matter determination with NaOH, and methylene blue experiments were performed in fine aggregates. The modified Proctor test, CBR test, and freeze-thaw test were performed on samples whose granulometry was adjusted according to design values. For this reason, aggregate from the İncirli quarry and marble waste from Yenipazar District were taken. With these materials, samples were prepared by the gradation of the base material. The required quality control tests for the base material of the THTS road superstructure were performed on these samples. The standards used in the experiments and the number of experiments performed are given in Table 4.

One important property affecting the foundation layer stability and density is aggregate gradation. Therefore, the proportions of different aggregate grains in the mixture are specified in the specifications with lower and upper limits. A sieve analysis experiment was conducted

Table 4. Number of experiments and standards used

Name of the experiment	Number of experiments performed	Standard utilized
Sieve analysis	5	TS 1900-1
Fragmentation resistance (Los Angeles)	2	TS EN 1097-2, AASHTO T 96
Weather resistance test ($MgSO_4$)	4	TS EN 1367-2
Specific weight and water absorption	4	TS EN 1097-6
Flatness index	2	TS EN 933-3
Organic matter (3% NaOH)	2	TS EN 1744-1
Clay lump and friable particles	2	ASTM C-142
Liquid limit	2	TS 1900-1
Plastic limit	2	TS 1900-1
Methylene blue	2	TS EN 933-9
Modified Proctor	25	TS 1900-1
CBR	20	TS 1900-2
Freezing-thawing	45	ASTM D6035

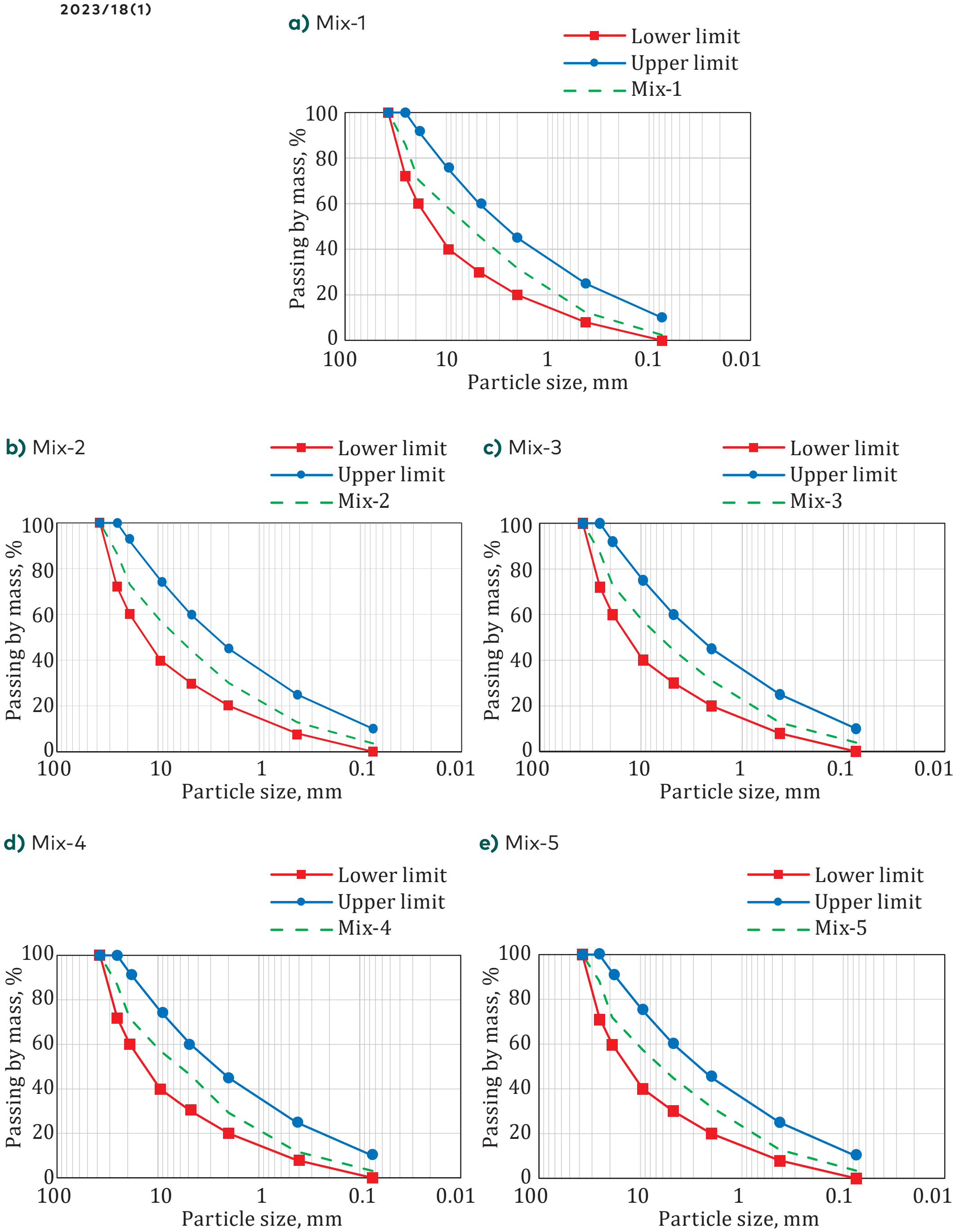


Figure 10. Gradation curves of mixtures: a) Mix-1; b) Mix-2; c) Mix-3; d) Mix-4; e) Mix-5

to investigate whether the foundation layer's material properties are within the specifications (Figure 10). The Los Angeles test measures the deterioration of the mineral aggregate's standard gradation due to the abrasion factors to which the aggregates are exposed. Since the aggregate degradation will cause segregation, the desired compression ratio cannot be achieved, and the road foundation exposed to traffic loads may collapse. Therefore, abrasion losses of aggregates to be used in road constructions should be within the specification limits. The test, known as weather resistance or resistance to freezing effects, provides aggregates against freezing and thawing using magnesium sulphate ($MgSO_4$). It is known that aggregates, which have been under the weather for a long time, undergo gradation deterioration due to freezing and thawing. Since gradation deterioration will also cause the road to deteriorate, aggregates must be resistant to frost and thaw events. Specific gravity is defined as the ratio of the weight of a material in the air at a given volume and temperature to distilled water in the air at the same volume and temperature. The water absorption capacity of aggregates is related to the ratio of their void volumes. As expected, the water absorption rate is high in aggregates with a hollow structure. Therefore, aggregates with a high water absorption rate will have low frost resistance. Aggregate to be used in highway construction are required to have a low water absorption rate to avoid low resistance.

The flatness index test is based on defining aggregate grains whose thickness is less than 0.6 of their nominal size as flat. The aggregates used in road construction are required to be crushed stone and not flat. Flat grains do not provide the desired strength since aggregates exposed to traffic loads will be exposed to pressures from all directions. Besides, the compression of flat grains is not at the desired level. The organic matter experiment with NaOH does not give a quantitative result and is an observational experiment. In the investigation, it is determined whether the aggregate samples contain organic matter or not. Since aggregates containing organic matter can give chemical reactions in their structure, they can cause deformations. The liquid limit of the samples is calculated from the experiments with the Casagrande instrument.

In contrast, the plasticity index is calculated based on the liquid limit and plastic limit test results. These experiments are carried out by adding water to the material passing through the sieve No 40 and bringing it to a dough consistency. The material liquidity and plasticity values are determined with this experiment, which can be applied to fine aggregates. Aggregates to be used in road ground constructions are required to be non-plastic. This is because the fine aggregates' plastic behaviour in the foundation soil will cause deformations in the foundation soil since the road foundations will be exposed to water intensively. Methylene blue test is performed to determine the pollution rate of aggregates. This experiment is carried out with aggregates passing through a 2 mm sieve. It is stated in the specifications that the pollution rate of aggregates to be used in the foundation layers of road constructions can be 3% at most because dirty aggregates reduce the resistance of the road foundation ground against traffic loads with the dirt layers contained.

1.3. Mechanical tests

It is thought that temporary deterioration in aggregates' carrying capacity after freezing expansion and thawing in cold, snowy regions accelerates decline in transportation facilities and their loss of functions (Ishikawa, 2015). The modified Proctor experiment aims to determine the water content that gives the highest dry unit weight (rdmax) in a soil compacted with the help of a specific method. For this purpose, the losses in the strength of the materials used in road construction due to freezing-thawing depending on the regional climate conditions were determined. Also, differences in percentage sieves after impact compaction of aggregate and marble waste were calculated.

2. Results and discussion

Turkish Highways Technical Specifications (2013) path normative superstructure experiments were applied to the base material and waste marble aggregate sample. Test results and criteria of Turkish Highways Technical Specifications (2013) are given in Table 5.

2.1. Physical tests

According to the determination of fragmentation resistance (Los Angeles method), the specification was below the material limit value. The fragmentation resistance of marble waste was 11% higher than the aggregate. In the weather resistance test, marble waste was 23% more durable than aggregate. The value obtained for both materials remained below the THTS limit value. According to the results obtained from the water absorption test, aggregate has 84% more water absorption rate than marble waste. Despite this difference, the values obtained remained below the THTS limit value. According to the results from the flatness index test, marble waste has a flat value of 14% compared to aggregate. The value obtained for both materials remained below the

THTS limit value. The determination of organic matter with NaOH was adverse in both materials, as predicted by THTS. The clay pellet value for fine aggregate was 33% higher for İncirli quarry aggregate than marble waste. The coarse aggregates of İncirli quarry value were 55% more than the coarse aggregates of the marble waste. The values obtained as a result of the experiment are below THTS limits for both materials. As a result of the liquid and plastic limits tests, the materials showed non-plastic properties as predicted by THTS. As a result of the methylene blue test, the methylene blue of İncirli quarry's aggregates value was 33% more than the marble waste aggregate. The value obtained for both materials remained below the THTS limit value.

Table 5. Comparison of test results

Name of the experiment		Unit	Aggregate	Marble waste	Criterion
Fragmentation resistance (Los Angeles)		%	19.46	21.68	≤35
Weather resistance test ($MgSO_4$)		%	3.24	2.50	≤20
Water absorption		%	0.35	0.19	≤3
Flatness index		%	12.81	14.64	≤30
Organic matter (3% NaOH)			Negatif	Negatif	Negatif
Clay lump fine aggregate		%	0.53	0.40	≤1
Clay lump coarse aggregate		%	0.17	0.11	≤1
Liquid limit			NP	NP	NP
Plastic limit			NP	NP	NP
Methylene blue		%	1	0.75	≤3
Modified Proctor (w_{opt} – γkmax)	Mixture-1	% - kN/m^3	4.50–23.25		
	Mixture-2	% - kN/m^3	4.50–22.80		
	Mixture-3	% - kN/m^3	4.56–22.99		
	Mixture-4	% - kN/m^3	4.58–22.97		
	Mixture-5	% - kN/m^3	4.55–22.80		
California Bearing Ratio Wet (CBR)	Mixture-1	%	286		≥120
	Mixture-2	%	213		
	Mixture-3	%	232		
	Mixture-4	%	265		
	Mixture-5	%	237		
CBR values after freeze-thaw (4 Cycle-12 Cycle-20 Cycle)	Mixture-1	%	431-241-161		
	Mixture-2	%	420-427-256		
	Mixture-3	%	316-322-222		
	Mixture-4	%	441-245-190		
	Mixture-5	%	446-335-291		

2.2. Mechanical tests

As a result of the modified Proctor test, the maximum dry unit weight (rdmax) value was observed in Mixture-1. This is because the flat and long aggregates in the material entering Mix-1 are less than the other mixtures. To achieve the same result, Kailash et al. (2013) reached in their study, Figure 11 shows given aggregate percentage of mixtures after compaction. The graphs given for each mixture showed that the passing percentages increased due to breakage.

The wet CBR values remained above the THTS limit, ensuring the specification values. All experimental results showed that all types of mixtures formed by substituting marble waste pieces in different size ranges instead of aggregate could be used as a base material in a highway superstructure. Likewise, Yakşe (2016), Ahmed et al. (2014), Fırat et al. (2012), and Mostafa (2016) studied the usability of marble waste fragments in road superstructures and concluded that marble waste could be used in road superstructures. Also, Kailash et al. (2013) conducted a study on the usability of limestone wastes in the road foundation layer instead of traditional aggregates such as basalt. According to the New Delhi MoRT & H-2001 specification, as shown in Table 6, the wet CBR values of all mixture types are higher than the dry CBR values. As a result of changing the water content in the environment from its optimum value to the saturation value, there was an increase in the CBR value of all the mixtures tested (Domitrovic et al., 2016).

Table 6. Comparison of CBR values

Curing time	Substituted material	Mixture No	Dry CBR, %	Wet CBR, %	4 Cycle CBR, %	12 Cycle CBR, %	20 Cycle CBR, %
0 days curing	Reference	Mixture-1	237	286	431	241	161
	0–5	Mixture-2	200	213	420	427	256
	5–12	Mixture-3	222	232	316	322	222
	12–19	Mixture-4	210	254	441	245	190
	19–38	Mixture-5	232	237	446	335	291
7 days curing	Reference	Mixture-1	278	321	356	293	187
	0–5	Mixture-2	220	246	227	201	187
	5–12	Mixture-3	236	254	265	211	198
	12–19	Mixture-4	244	263	291	195	189
	19–38	Mixture-5	243	274	287	255	226

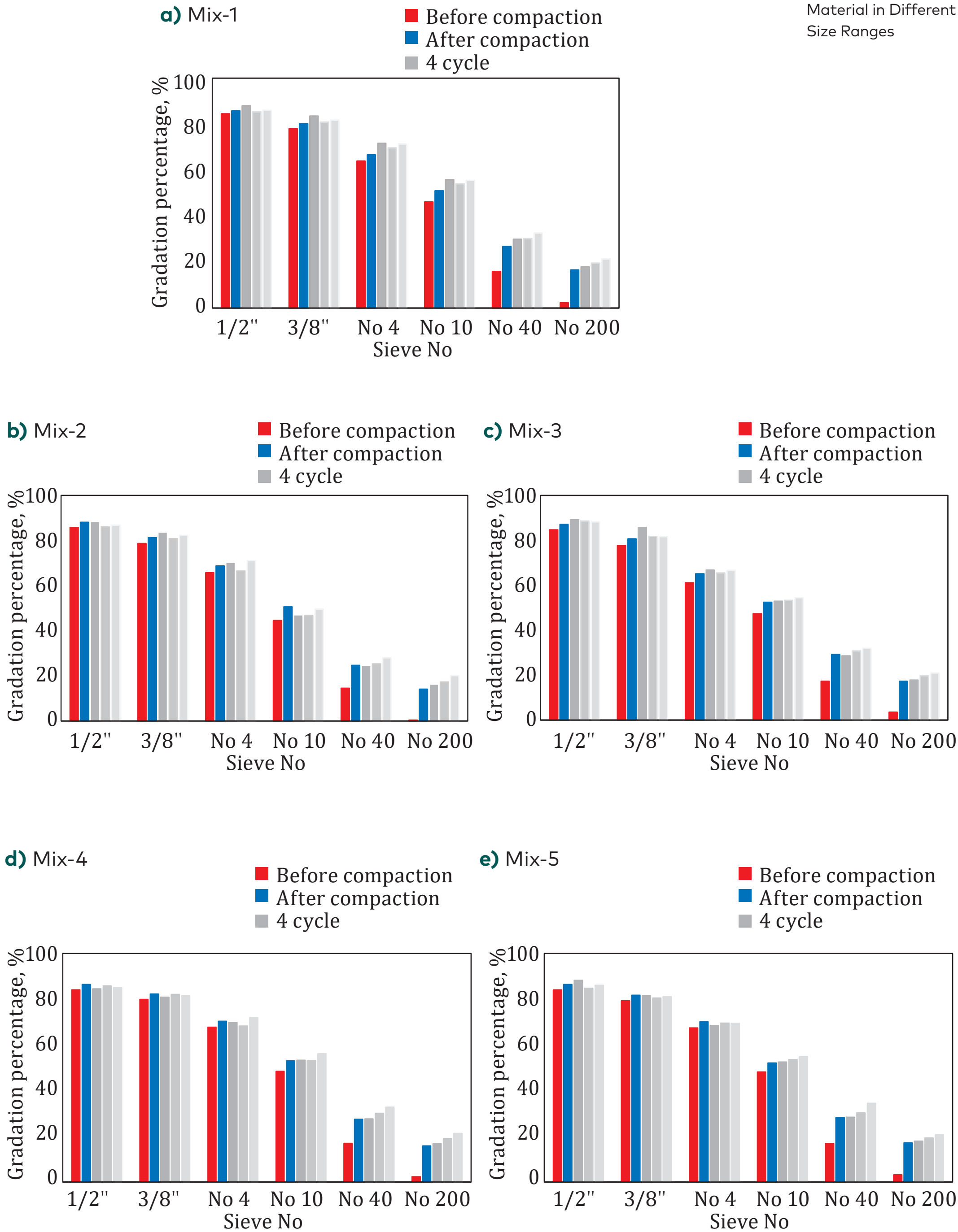


Figure 11. Aggregate percentage of mixtures after compaction and freeze-thaw: a) Mix-1; b) Mix-2; c) Mix-3; d) Mix-4; e) Mix-5

The effect of water content on the CBR value depends mainly on the natural aggregate (Domitrovic et al., 2016). The most significant change in CBR value from Table 7 was experienced in Mixture-1 consisting of aggregate. When the dry and wet CBR values were compared, the CBR value of Mix-1 sample, which was taken as the reference, was higher than all other mixture types. This state can be explained by the low Los Angeles abrasion value and the low flatness index value of the reference material. Los Angeles provides information about the abrasion value and the loss in strength resulting from the splits that will occur in the face of abrasion and impacts. This value is desired to be below to minimize strength losses. As a result of the abrasion test, marble waste showed 11% more wear than aggregate. Due to this difference between the two materials, the CBR value of the reference material was higher than the other mixtures (Mix-2, Mix-3, Mix-4, Mix-5) containing marble waste pieces. When looking at the flatness index, the flatness index value of the reference material was lower than the flatness index value of samples created for other mixtures. This decrease is due to the inclusion of marble waste pieces with a higher flatness index value than the flatness index value of the reference material in the mixtures other than the reference material (Mix-2, Mix-3, Mix-4, Mix-5). Therefore, the CBR value of the reference material was higher than that of the mixtures (Mix-2, Mix-3, Mix-4, Mix-5) formed with marble waste.

When the dry and wet CBR values of the mixtures are compared as a result of 0 days and 7 days of curing, the lowest values are generally reached in Mix-2. This is thought to be due to the 0–5 mm marble waste fragments entering the Mix-2 at a rate of 44%. Considering the Mix-2 formed, it was observed that 0–5 mm material could not provide interlocking with aggregate materials in other ranges starting the mixture. The marble waste material of 0–5 mm in this mixture

Table 7. Change in dry and wet CBR values

	0 Days curing				
	Mixture-1	**Mixture-2**	**Mixture-3**	**Mixture-4**	**Mixture-5**
CBR(omc)	237	200	222	210	232
CBR(96h)	286	213	232	254	237
ΔCBR%	21	7	5	21	2
	7 Days curing				
	Mixture-1	**Mixture-2**	**Mixture-3**	**Mixture-4**	**Mixture-5**
CBR(omc)	278	220	236	244	243
CBR(96h)	321	246	254	263	274
ΔCBR%	15	12	8	8	13

Table 8. Water content of samples by the number of freeze-thaw cycles

Cycle No	Curing time	Instant					7 Days				
	Mixture	M-1	M-2	M-3	M-4	M-5	M-1	M-2	M-3	M-4	M-5
	Optimum water content (w_{opt})	4.50	4.50	4.56	4.58	4.55	4.50	4.50	4.56	4.58	4.55
0	Bottom surface (w_b)	4.41	4.48	3.98	3.87	3.72	3.76	4.18	4.26	3.47	4.15
	w_b–w_{opt}	–0.09	–0.02	–0.58	–0.71	–0.83	–0.74	–0.32	–0.30	–1.11	–0.40
	Top surface (w_t)	5.56	4.45	4.75	4.53	4.25	5.16	4.47	4.54	4.03	5.04
	w_t–w_{opt}	1.06	–0.05	0.19	–0.05	–0.30	0.66	–0.03	–0.02	–0.55	0.49
	Average (w_a)	4.99	4.47	4.37	4.20	3.99	4.46	4.33	4.40	3.75	4.60
	w_a–w_{opt}	0.48	–0.04	–0.19	–0.38	–0.57	–0.04	–0.18	–0.16	–0.83	0.05
4	Bottom surface (w_b)	4.15	3.49	4.37	4.68	4.12	4.65	3.64	4.00	4.41	4.21
	w_b–w_{opt}	–0.35	–1.01	–0.19	0.10	–0.43	0.15	–0.86	–0.56	–0.17	–0.34
	Top surface (w_t)	4.48	3.75	5.53	4.58	4.60	5.43	4.05	4.77	5.04	4.70
	w_t–w_{opt}	–0.02	–0.75	0.97	0.00	0.05	0.93	–0.45	0.21	0.46	0.15
	Average (w_a)	4.32	3.62	4.95	4.63	4.36	5.04	3.85	4.39	4.73	4.46
	w_a–w_{opt}	–0.19	–0.88	0.39	0.05	–0.19	0.54	–0.66	–0.18	0.15	–0.09
12	Bottom surface (w_b)	5.43	4.64	5.06	4.81	4.57	4.83	4.28	4.16	4.92	4.64
	w_b–w_{opt}	0.93	0.14	0.50	0.23	0.02	0.33	–0.22	–0.40	0.34	0.09
	Top surface (w_t)	6.11	4.46	6.93	5.87	5.66	4.95	4.29	5.59	5.38	6.82
	w_t–w_{opt}	1.61	–0.04	2.37	1.29	1.11	0.45	–0.21	1.03	0.80	2.27
	Average (w_a)	5.77	4.55	6.00	5.34	5.12	4.89	4.29	4.88	5.15	5.73
	w_a–w_{opt}	1.27	0.05	1.44	0.76	0.57	0.39	–0.22	0.32	0.57	1.18
20	Bottom surface (w_b)	5.96	4.94	5.51	6.98	5.04	5.74	5.74	5.51	5.39	4.91
	w_b–w_{opt}	1.46	0.44	0.95	2.40	0.49	1.24	1.24	0.95	0.81	0.36
	Top surface (w_t)	6.59	4.68	6.07	6.52	6.50	6.28	6.28	5.70	6.42	6.70
	w_t–w_{opt}	2.09	0.18	1.51	1.94	1.95	1.78	1.78	1.14	1.84	2.15
	Average (w_a)	6.28	4.81	5.79	6.75	5.77	6.01	6.01	5.61	5.91	5.81
	w_a–w_{opt}	1.78	0.31	1.23	2.17	1.22	1.51	1.51	1.05	1.33	126

was not a binding material. This feature caused the samples not to be compressed in the desired proportions. The CBR values reached due to this situation remained lower than the CBR values of other mixture types.

In this study, all CBR experiments were performed on mixtures (M-1, M-2, M-3, M-4, M-5) prepared according to the optimum water contents (w_{opt}) found due to the modified Proctor test. The water contents found after the CBR test are given in Table 8. At the end of the 0-day curing and 4th cycle, as stated in the THTS, the water content of the mixtures remained within the $w_{opt} \pm 2$ limit values. These limit values were obtained at the end of the 12th and 20th cycles. The increase in water content with the rise in freeze-thaw cycles effectively achieved these results. The schematic of water movement in grain pores due to freezing is shown in Figure 12 (Kawabata et al., 2016). When the aggregate grains are exposed to low temperatures, the grain surface temperature is low, and the internal temperature at the initial phase is high. This results in a temperature gradient in the grain. This temperature gradient causes water to flow in the direction of thermal flow. As time passes, the temperature in the grain stabilizes, and the movement of the water ends. If thawing occurs under these conditions, the pore water content on the grain surface increases compared to the initial situation, and re-freezing causes additional water accumulation around the surface (Kawabata et al., 2016). The change in CBR values due to the number of freeze-thaw cycles is given in Table 9 (Domitrovic et al., 2016). Figure 10 shows given aggregate percentage of mixtures after freeze-thaw. The graphs given for each mixture show that the passing percentage increases due to freeze-thaw.

Freeze-thaw resistance mainly depends on the internal and external parameters of the aggregate. Porosity, water content, and undissolved salts significantly affect the performance of aggregate exposed to freezing (Yates & Mauko, 2008; Lindqvist et al., 2007). Expanded pore water due to freezing can generate significant pressures that can cause aggregate wear and breakage and cause degradation in the road foundation layers, contributing to a decrease in rigidity (Arm, 2001; Rosa, 2006). Considering the number of freeze-thaw cycles (Table 9), an increase occurred in CBR values of all mixture types at the end of the 4th cycle. Since the CBR value is a concept related to the material strength, the increase will only be possible with an increase in the material strength or better compression. Since no situation will cause an increase in the strength of the material during the freezing-thawing process, the CBR value will cause a slight increase in the compression value with the movement of the aggregates small amount. In the study conducted by Kawabata et al. (2016) and Soleimanbeigi et al. (2015), it

Table 9. Freeze-thaw CBR values at the end of 0- and 7-days curing

		0 Day curing			
		Instant	**4 Cycle**	**12 Cycle**	**20 Cycle**
Mixture-1	CBR(omc)	237	431	241	161
	ΔCBR%		82	2	–32
Mixture-2	CBR(omc)	200	420	427	256
	ΔCBR%		110	114	28
Mixture-3	CBR(omc)	222	316	322	222
	ΔCBR%		42	45	0
Mixture-4	CBR(omc)	200	441	245	190
	ΔCBR%		121	23	–5
Mixture-5	CBR(omc)	232	446	335	291
	ΔCBR%		92	44	25
		7 Day Curing			
		Instant	**4 Cycle**	**12 Cycle**	**20 Cycle**
Mixture-1	CBR(omc)	278	356	293	187
	ΔCBR%		28	5	–33
Mixture-2	CBR(omc)	220	227	201	187
	ΔCBR%		3	–9	–15
Mixture-3	CBR(omc)	236	265	211	198
	ΔCBR%		12	–11	–16
Mixture-4	CBR(omc)	244	291	195	189
	ΔCBR%		19	–20	–23
Mixture-5	CBR(omc)	243	287	255	226
	ΔCBR%		18	5	–7

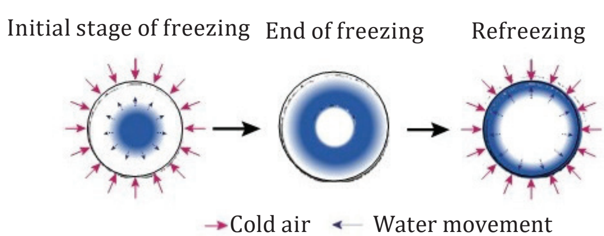


Figure 12. Movement of particle pore water due to freezing (Kawabata et al., 2016)

was stated that there was an increase in volume as a result of freezing and that the volume increase in this process was forced into the spaces due to freezing of the water in the grain pores and the aggregate grains would move somewhat. They stated that this physical state would change the space structure and affect the CBR value (Soleimanbeigi et al., 2015; Kawabata et al., 2016). At the end of 12 and 20 cycles, CBR values generally decreased. The most significant decrease occurred in the reference material, Mix-1. It is thought that this decrease causes the movement of the grains to be greater as a result of the volume expansion of the water in the material and causes rupture and capillary cracks on the edges of the grains. This has a negative effect on the strength of the material. This decrease in strength caused a reduction in CBR values. Similarly, Yates & Mauko (2008) observed that fine cracks occurred in the material at the end of the 12th cycle.

As shown in Table 7, water content of the sample increased with the number of cycles. The water content shown in Table 8 for the 12th and 20th cycles is usually higher. This increase in water content caused a more significant decrease in the material strength due to freezing. It was observed that the ruptures and cracks experienced in the material continued until the end of 20 cycles, and the CBR values gradually decreased. Similarly, Kawabata et al. (2016) stated that the interior of the road pavement froze during the winter in cold regions, and the volume increase in the substrate soil caused friction and cracks. They explained that the thawing of the road substrate exposed to the volume expansion due to the frost caused a decrease in the coating bearing capacity and deterioration. As a result of 0 days and 7 days curing, the most significant decrease in the CBR value between 4 and 20 cycles was experienced in Mixture-1, which is the reference material. The reduction in the CBR value is thought to be due to the low strength resulting from the rupture and cracking caused by freeze-thaw on the grains.

According to the water absorption test results, aggregate has a 45.7% more water absorption rate than marble waste. The water absorption rate of the aggregate material constituting the Mixture-1 is higher than that of other mixtures containing marble waste fragments. Aggregate grains with a high water absorption rate will be exposed to more rupture and cracking due to freezing by having more water. The high rates of these ruptures and cracks caused the CBR value of the reference mixture to decrease more than the other mixtures (Mix-2, Mix-3, Mix-4, and Mix-5). Table 11 summarises the decrease in carrying capacity due to freeze-thaw effects. Grain pore water moves to the grain surface as a result of freezing. This causes changes in the friction and space structure between the grains. The difference varies with the water content, and if only the intergranular friction changes, the reduction in carrying capacity can be reversed. However, if the cavity structure is changed significantly, the carrying capacity does not recover (Kawabata et al., 2016).

3. Cost analysis

Crushed stone aggregates obtained from quarries are used as base materials in road constructions. The costs of obtaining these materials and their transportation costs constitute a large budget. For this reason, materials procured in proximity to the manufacturing site cause a significant reduction in construction costs. The cost of obtaining natural aggregate from a quarry consists of items such as using explosives in the quarry, crushing the stone obtained from the quarry with a compressor, loading it with a wheel loader, crushing and sifting in the crusher, loading it into vehicles, and shipping it to the construction site. Cost of these items was calculated by taking into account the 2019 unit prices of the General Directorate of Highways, Turkey, 2019 for natural aggregate (Table 12).

The unit cost of 1 m^3 base material obtained from natural aggregate was 38.43 TL/m^3, excluding transportation. Assuming that the bulk unit weight of natural aggregate is 1.6 t/m^3 on average, the unit cost of 1-ton base material was calculated as 24.02 TL/t (TL – Turkish currency).

The cost calculations of marble waste include loading with a wheel loader, separating it into diameters by sieving, breaking it in the crusher, loading it into the transport vehicle, and transporting to the construction site. The unit cost of 1 m^3 base material produced from marble waste was calculated as 18.78 TL/m^3, excluding transportation, with the unit prices for 2019. Assuming that the bulk unit weight of marble waste is 1.56 t/m^3 on average, the unit cost of one ton of base material was calculated as 12.04 TL/t. The unit cost of 1-ton base material obtained from natural aggregate, excluding transportation, was 24.02 TL. The unit cost of one ton of base material obtained by utilizing marble waste was 12.04 TL, excluding transportation. There is an approximately two-fold difference between the unit cost of the material obtained from marble waste and the unit cost of the natural aggregate material.

If we calculate how many kilometres the unit price difference between these two materials will correspond to the transportation distance, transport Equation (1) for transports with $M > 10$ km is as follows:

$$F = 1.25 \times A \times K \times (0.0007 \times M + 0.01), \quad (1)$$

where F is a unit price, A is a road condition coefficient, K is a transport coefficient unit price, and M is distance.

K coefficient for the year 2019, for which the analysis was conducted, is 330.00 TL according to the Ministry of Environment and Urbanization (2019), and A coefficient for the Yenipazar district is 1.25 according to the Special Provincial Administration Commission Report for Bilecik (Special Provincial Administration Commission Report for Bilecik, 2019). The formula calculated the 18.9 km transportation distance. This result can be called the economic equality distance for marble waste and natural aggregate, i.e., using marble waste by bringing marble waste from 18.9 km away will give the same cost as using natural aggregate, even if there is a quarry in the construction site for a road construction site 18.9 km away. If the distance between the construction site and the marble quarry is less than 18.9 km, using marble waste as the base material will decrease the material unit price, thus resulting in economic gain.

According to the results obtained in a study conducted on 35 companies in Bilecik province (Kacır, 2017), one company creates 35 tons of marble waste per day. Considering that a company works an average of 25 days a month, the amount of waste released is 875.00 (= 35 × 25) t/month. The total amount of waste generated by 35 companies is 30 625 (= 35 × 875.00) t/month. According to the geometric standards of highways (Turkish Highways Technical Specifications, 2013), if a 20 cm Type-1 PM foundation layer is laid on a two-lane road with a platform width of 12 m through the city, the amount of material required for 1-meter road construction was calculated with the help of equation (2).

$$\text{Required material} = \text{platform width} \times \text{thickness} \times \text{specific weight} \qquad (2)$$

Required material calculated by Eq. (2) is 6336.00 t/m. According to this result, the foundation layer of a road of approximately 4833 m can be manufactured with 30 625 tons of material. The high number of marble quarries in Bilecik province will contribute to both the companies that will make the road and our country's economy by using marble waste on the roads to be built in this province.

Conclusions

This study has investigated the appropriateness of substituting the marble waste obtained from a marble quarry in the Yenipazar district of Bilecik province instead of the aggregate, which all the time is used in the base layer in highway construction. The results of the analysis and experiments have been compared with the standard values specified in THTS (2013), and the following results have been obtained.

- The mixture gradations created according to the sieve analysis remain between the lower and upper limits specified in the THTS.
- The fragmentation resistance has been determined according to the Los Angeles abrasion test method, and aggregate and marble waste meet the THTS requirements.
- Weather resistance has been determined, and aggregate and marble waste values fulfil this condition for THTS requirements.
- The flatness index has been determined, and both materials provide THTS values.
- Water absorption and specific gravity test results have been determined, and aggregate and marble waste values fulfil THTS requirements.
- According to the organic matter detection test, results with NaOH show no colour change in the NaOH solution in both materials. It has been determined that there is no organic matter in the materials. With this result, both materials show the desired feature in THTS.
- The clay pellet test has been conducted, and both materials provide THTS values.
- In the plastic limit test, it has been determined that aggregate and marble waste materials are not plastic. With this feature, aggregate and marble waste have been found by THTS data.
- The methylene blue test has been conducted, and both materials provide THTS values.
- Modified Proctor experiments have been carried out with the mixtures formed for the Type-1 PM base layer. Optimum water contents (w_{opt}) and maximum dry unit volume weight (rdmax) have been determined for each mixture. Also, it is seen that the passing percentage increases due to breakage.
- CBR samples have been prepared using these values obtained, and CBR experiments have been performed 0 day and at the end of 7 days of curing. All mixture types remain above this value and fulfil the specifications for THTS.
- According to the freeze-thaw test results, there is an increase in CBR values in the first 4 cycles and a decrease in the following cycles. According to all the test results, marble waste has been found suitable for aggregate in the foundation layer of the flexible highway superstructures that meet the criteria specified in THTS (2013). Also, it is seen that the passing percentage increases due to freeze-thaw.
- Aggregate unit cost constitutes approximately twice the unit cost of marble waste. Besides, this difference has created an economic equality distance of 18.9 km. Therefore, a marble quarry, a road

construction site within the calculated economic equality distance and marble waste material will provide financial gain for our country.

– According to the amount of waste generated per company on 35 companies for Bilecik, the waste marble amount has been calculated for a month. As a result of the calculation, it is seen that with the marble waste obtained per month, the foundation layer of a 4.8 km road could be produced. Such an amount can be calculated for each region in different countries. Thus, we can leave a liveable world with rich raw material resources and a strong economy for future generations.

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