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Research Article

A study on investigating the effect of lignosulfonate-based compaction aid admixture dosage on the properties of roller compacted concrete

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Abstract: In this study, roller compacted concrete was produced by using a modified lignosulfonate-based chemical admixture which is suitable for use in wet, semi-dry or zero slump concrete, and the effect of admixture dosage on the physical and mechanical properties of the concrete was investigated. In the production of roller compacted concrete, the cement content was 300 kg/m^3 and the chemical admixture dosages have been changed as 0%, 0.3%, 0.6% and 0.9%. Percentage of compactibility, total water absorption, unit weight, ultrasonic pulse velocity, dynamic modulus of elasticity, concrete compressive strength at the ages of 3 and 28 days were determined for the roller compacted concrete specimens. Roller compacted concrete with the lowest percentage of water absorption, the highest percentage of compactibility, ultrasonic pulse velocity, compactness, compressive strength and dynamic modulus of elasticity was the concrete produced with 0.6% admixture dosage. With the concrete design and the chemical admixture in question, it has been observed that the optimum dosage of chemical admixture for the production of the best quality concrete in terms of the concrete properties examined was 0.6%.

Keywords: Admixture dosage, chemical admixture, mechanical properties, physical properties, roller compacted concrete.

1. Introduction

Roller compacted concretes are concretes with a dry consistency and zero slump, often preferred in road and dam applications, and stand out with their advantages such as being able to be constructed and put into use quickly. As in conventional concrete production, the use of chemical or mineral admixtures, water/cement ratio, cement type and cement content, concrete mix design affect mechanical properties of roller compacted concretes (Yazici, 2008; Kilic and Gok, 2021a). Roller compacted concretes exhibit different properties compared to normal concrete, as they are much drier concretes. Although various admixtures used in conventional concrete can also be used in these concretes, it may be necessary to change the admixture dosage in order to achieve the targeted concrete performance. According to Hazaree (2010), higher dosages of chemical admixtures are needed in the production of roller compacted concrete compared to conventional concrete. On the other hand, excess use of admixtures may affect concrete properties negatively. The excess use of superplasticizers causes the presence of excess water that fills the pore volume, this water leaves the voids in the hardened roller compacted concrete matrix by drying, and then microcracks develop in the concrete during loading, premature fracture occurs and bending strength reduces (Adamu et al., 2017a). Addition of plasticizers in roller compacted concrete decreases the concrete porosity, creates a denser concrete structure, and increases the thermal conductivity of concrete (Hashemi et al., 2020).

As roller compacted concretes are dry concretes, casting and leveling processes differ from normal concrete, these concretes need to be compacted in order to reach their final form (Hosseinnezhad et al., 2021; Kilic and Gok, 2021b; Gok et al., 2021). Appropriate consistency must be provided in these concretes so that the compression machine is not forced too much and the compression energy can be reduced (Chhorn and Lee, 2017). Workability of concrete is affected by the cohesion, compactibility, resistance to segregation, workability retention, water reduction and consistency; the improvement in workability of a mixture varies depending on the internal friction angle, the amount of voids in the concrete, the type and dosage of the admixture used in concrete (Hazaree, 2010; Hazaree et al., 2010).

Mineral admixtures (e.g. fly ash, silica fume, rice husk ash) can be used to improve some fresh and hardened concrete properties in roller compacted concretes, as well as steel or polypropylene fibers and chemical admixtures (e.g. water reducers, accelerators, retarders, etc.) (Harrington et al., 2010; Modarres and Hosseini, 2014; Pektas, 2015; Sengun et al., 2017; TCMB, 2018; Nero, 2019; Yetim and Yilmaz, 2019; Shen et al., 2020; Hashemi et al., 2020; Mardani-Aghabaglou et al., 2020; Kilic and Gok, 2021c). Since super plasticizers reduce the water requirement in concrete mixture, the compressive strength increases due to the decrease in the water/cement ratio with the use of super plasticizers (Kilic, 2014). In roller compacted concretes, water-reducing admixtures are used to improve workability, increase the consistency, decrease the water/binder ratio and increase the concrete strength by helping the dispersion of the cement paste (Adamu et al., 2017b). Apart from these admixtures, studies have also been conducted on the use of cationic asphalt emulsion as an admixture in roller compacted concrete production (Dareyni et al., 2018).

According to the Concrete Roads Technical Specification, air-entraining, water-reducing, high-range water-reducing, set-retarding admixtures and long workability admixtures are used in the manufacture of concrete pavements (KGM, 2016). The chemical admixtures used to improve concrete properties should comply with TS EN 934-1 (2010) and TS EN 934-2 (2013) standards. Although the use of mineral and/or chemical admixtures is not required in roller compacted concrete production, it is preferred to improve some fresh and hardened properties of concrete (Engin et al., 2019). On the other hand, if more than one chemical admixture will be used together in the production of roller compacted concrete, the compatibility and interaction of the admixtures with each other should be investigated beforehand with trial productions, some types and dosages of admixtures may not be suitable for RCC production and may adversely affect concrete properties (Nero and Haldenbilen, 2020). Since roller compacted concrete is a newer building material than conventional concrete, research on this subject gains importance and more research is needed to explain mechanisms that affect concrete properties.

As it is known, chemical admixtures must be used in appropriate dosages to show the best performance in conventional concrete. Roller compacted concretes are concretes with a much drier consistency compared to conventional concretes. In order for the chemical admixture to achieve the desired effect in the concrete, it must be dissolved in water and dispersed as homogeneously as possible in the concrete, it may be difficult to achieve this in dry concretes. When the water/cement ratio is below a certain limit, the expected increase in compressive strength cannot be achieved due to problems in compaction, settlement and workability (Kilic and Gok, 2022).

Lignosulfonate-based admixtures are a good choice in roller compacted concrete, in terms of cost and technical aspects. These admixtures can be used in the production of RCCs, it is one of the suitable admixtures. On the other hand, excessive use of these admixtures can cause a delay in setting. These admixtures are suitable for use in hot weather concreting. Preliminary testing is particularly important in working with supplementary cementitious materials (SCMs), as studies on its use with SCMs are limited. In cold weather, it may cause delay in setting and decrease in strength gain rate. With these admixtures, compaction can be improved as a function of admixture dosage and water reduction capacity. Finishing can still be an issue when using this admixture, as it does not provide an improvement in surface finish (Hazaree et al., 2010). In this experimental study, a lignosulfonate-based admixture was preferred in production of roller compacted concrete because it helps compaction, provides technical advantages and is cost-effective. Furthermore, it has been reported that lignosulfonate-based admixtures have been used as water-reducers and plasticizers in concrete since the 1930s, as they have been used for a long time, many studies have been conducted on them and they can improve concrete properties with their working mechanisms (Scripture, 1937; Swenson and Thorvaldson, 1959; Gelardi and Flatt, 2016; Gelardi et al., 2016; Magina et al., 2021).

The studies investigating the effects of chemical admixtures on roller compacted concrete are limited. In this research, it was aimed to examine the effect of compaction aid admixture dosage on roller compacted concrete properties and to investigate the optimum dosage of admixture in order to improve roller compacted concrete quality. For this purpose, roller compacted concrete was produced by using modified lignosulfonate-based chemical admixture which is suitable for use in wet, semi-dry or zero slump concretes, and the effect of admixture dosage on the physical and mechanical properties of the concrete was investigated. In the production of roller compacted concrete, the cement content was 300 kg/m^3 and the chemical admixture dosages have been changed as 0%, 0.3%, 0.6% and 0.9%. Compactibility, total water absorption, unit weight, ultrasonic pulse velocity, dynamic modulus of elasticity (E), concrete compressive strength at the ages of 3 and 28 days were determined in the roller compacted concretes.

2. Materials and methods

2.1. *Materials*

In production of roller compacted concretes, CEM I 42.5 R Portland cement, Kirklareli (Türkiye) tap water, crushed stone I, crushed stone II, natural sand and stone dust were used.

2.1.1. Cement

For the cement, initial setting time is 210 minutes, final setting time is 270 minutes, volume expansion is 2.0 mm, specific surface area (Blaine) is 4185 cm^2/g, 7-d and 28-d compressive strengths are 51.7 MPa and 59.3 MPa (Tracim, 2021). The chemical composition of the cement was given in Table 1. The specific gravity of the cement was 3.12.

Table 1. Chemical composition of Portland cement (wt%) (Tracim, 2021).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI
CEM I 42.5 R	18.57	4.43	2.86	63.55	0.91	3.15	4.34

2.1.2. Aggregates

The specific gravity of the aggregates was determined in accordance with TS EN 1097-6 (2013). The specific gravities of the aggregatates used in concrete production were given in the Table 2. Crushed stone I, crushed stone II and stone dust used in roller compacted concrete were dolomite origin aggregates.

Sieve analysis of aggregates was carried out in accordance with TS EN 933-1 (2012) and given in Figure 1. Maximum aggregate size (dmax) was 16.0, 12.5, 4.0 and 4.0 mm for crushed stone II, crushed stone I, stone dust and natural sand, respectively. While determining the grain size distribution of the aggregate mixture, the lower and upper limits for RCC production, which were recommended by Harrington et al. (2010), were used. As seen in Figure 1, mix ratios for each aggregate were determined so that the mixture granulometry remained between the lower and upper limits proposed.

Table 2. Specific gravities of the aggregates used in concrete production.

	Crushed stone II	Crushed stone I	Stone dust	Natural sand
Specific gravity	2.80	2.80	2.80	2.75

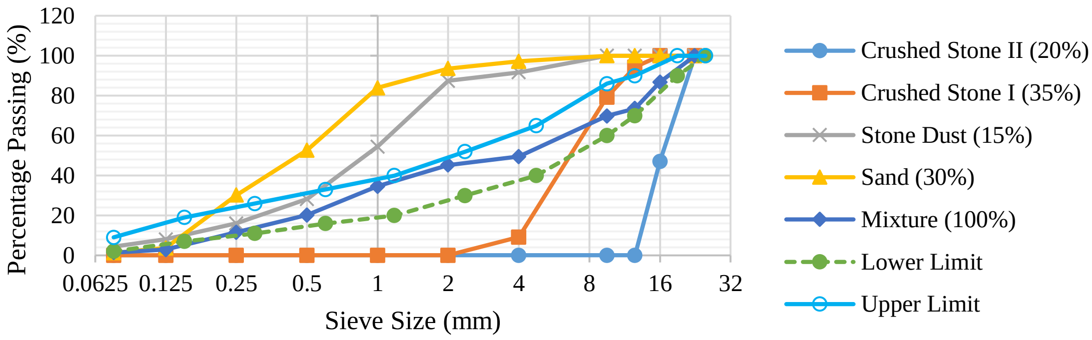

Figure 1. Sieve analysis.

2.1.3. Chemical admixture

The properties of the chemical admixture were given in the Table 3.

Table 3. The properties of the chemical admixture (Sika, 2021).

	Property
Appearance/color	Brown liquid
Chemical base	Modified lignosulfonate
Density	1.16±0.02 kg/l
pH	7±1 at 23.2°C
Recommended dosage	0.2%-0.6% of cement weight

2.2. *Concrete mix design*

Concrete mix design was given in the Table 4. In Table 4, C0 represents the reference concrete that was produced without using any chemical admixture. Water/cement ratio of the reference concrete is 0.34. C3, C6 and C9 represent the concrete mixes with 0.3%, 0.6% and 0.9% admixture dosage, respectively. Admixture dosage was expressed in % by mass of cement. In concrete design, the water/cement ratio was kept constant and the admixture amount was subtracted from the total amount of water to be used, and the amount of water in the mixture was obtained. Roller compacted concrete specimens were produced by using modified lignosulfonate-based chemical admixture at different dosages, as 0.3%, 0.6% and 0.9% of cement weight. The total aggregate mixture consists of 20% crushed stone II, 35% crushed stone I, 15% stone dust and 30% natural sand by weight.

Table 4. Concrete mix design.

Concrete Code	Water (kg)	Cement (kg)	Natural sand (kg)	Stone dust (kg)	Crushed stone I (kg)	Crushed stone II (kg)	Chemical admixture (kg)
C0	102.0	300	661	337	785	449	-
C3	101.1	300	661	337	785	449	0.9
C6	100.2	300	661	337	785	449	1.8
C9	99.3	300	661	337	785	449	2.7

2.3. *Methods*

Concrete mix design was carried out according to TS 802 (2016), slump test on fresh concrete was carried out according to TS EN 12350-2 (2019) standard. The fresh roller compacted concrete mixtures had dry consistency (Figure 2) and zero slump.

The RCC mixture at the fresh state was shown in Figure 2.

Figure 2. RCC mixture at the fresh state.

According to TS EN 12350-3 (2019), the allowable time interval for the Vebe test to be performed is given as 5 s ≤ Vebe time ≤ 30 s. This method was not used because the Vebe time was more than 30 seconds in RCC mixtures produced, and the mixtures were very dry. On the other hand, in order to be able to make a comparison about the consistency, slump test was carried out and the slump value was measured as zero in all RCC mixtures. The production of roller compacted concrete specimens was carried out in accordance with the ASTM C1435 (2020) standard. As shown in Figure 3, the compaction process was done by using specially produced heads that are compatible with the standard cube molds. 15 cm×15 cm×15 cm sized cube specimens were compacted with a vibrating hammer (Figure 3a) in a monolayer for 15 seconds.

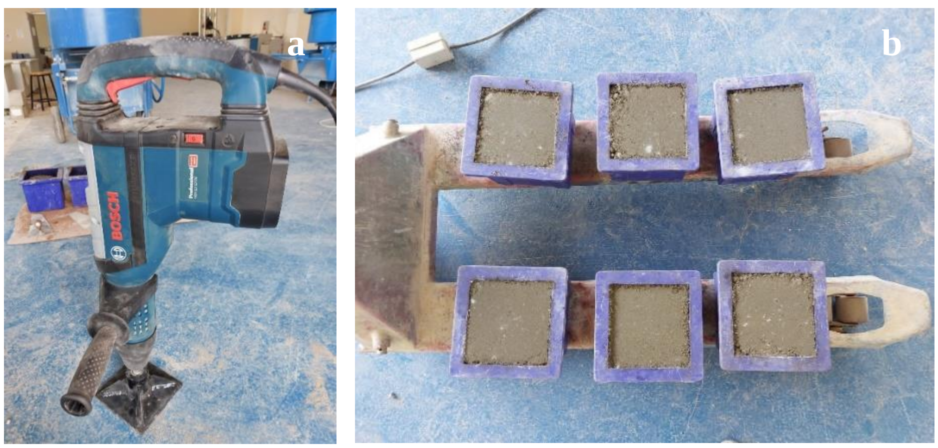

Figure 3. (a) Vibrating hammer (b) Specimens after compaction.

Since cold joint formation was encountered in the compaction operations that was performed in multilayers, compaction in a single layer has been preferred. The specimens after compaction were shown in Figure 3b.

As calculating the percentage of compactibility in the RCC specimens, standard cube molds were filled with concrete mix up to the upper level, compacted for 15 seconds after leveling, and the gap depth formed at the end of compaction was measured from the middle points of the four edges of the mold. After this measurement, the mean value was calculated, and the percentage of compactibility of the RCC specimen was determined by proportioning the determined mean value to the inner edge length of the 15 cm×15 cm×15 cm sized cube mold.

Roller compacted concrete specimens were demolded 24 hours after casting and water cured at 20±2°C until testing time.

In order to determine the compressive strength of roller compacted concretes, cube specimens at the ages of 3 and 28 days were tested according to the TS EN 12390-3 (2019) standard. Three specimens were tested for each experimental group and the mean values were determined. The loading rate was 0.602 MPa/s in uniaxial compression test (Figure 4).

Figure 4. Uniaxial compression test.

Total water absorption of RCC specimens at the age of 28 days were determined in accordance with BS EN 772-11 (2011) standard. The weights of the roller compacted concrete specimens, which were dried at 105°C in a drying-oven for 48 hours and reached a constant weight, were recorded, then these specimens were kept in water for 24 hours and water absorption percentages were calculated.

Unit weight test was conducted, the average dry unit weight and the average saturated unit weight were determined for each concrete mix.

Ultrasonic pulse velocity (UPV) of RCC specimens at the age of 28 days were measured in accordance with ASTM C597 (2016) and dynamic modulus of elasticity of the specimens were determined by using Proceq brand Pundit PL-200 ultrasonic test device. In these experiments, cube RCC specimens with a size of 15 cm×15 cm×15 cm were used. Three specimens from each series were tested and mean values were given in results section.

3. Experimental results and discussion

The percentages of compactibility were given in Table 5.

Table 5. Compactibility.

Concrete Code	Compactibility (%)
C0	10.11
C3	9.63
C6	12.22
C9	12.15

Specimens with 0.6% chemical admixture dosage had the highest percentage of compactibility. Compared to the reference concrete, the compactibility decreased by 4.75% with the use of 0.3% chemical admixture. On the other hand, with the use of 0.6% chemical admixture, the compactibility increased by 20.87%. When 0.9% chemical admixture was used, the increase in compactibility was 20.18%. In this study, a different method was used to make a comparison between roller compacted concrete in terms of compactibility. On the other hand, similar results were obtained with previous laboratory studies (Kilic and Gok, 2021d).

The mean compressive strengths (Figure 5) and coefficients of variation (CoV) of RCC specimens at the ages of 3 and 28 days were given in Table 6. Since the coefficients of variation are small, it can be said that the distribution is homogeneous and an accurate evaluation can be made with the data obtained. When the 3-day concrete compressive strengths were examined, it was seen that the reference specimens produced without the use of admixtures had the lowest compressive strength.

At the age of 3 days, the highest compressive strength had been reached with the use of 0.6% chemical admixture. The 28-day compressive strength results also showed a similar trend.

Table 6. Compressive strength.

Concrete Code	3-d (MPa)	$CoV_{(3-d)}$ (%)	28-d (MPa)	$CoV_{(28-d)}$ (%)
C0	26.83	1.01	29.93	8.70
C3	32.90	1.43	41.09	5.03
C6	41.96	1.42	46.89	5.89
C9	34.91	3.36	41.67	1.64

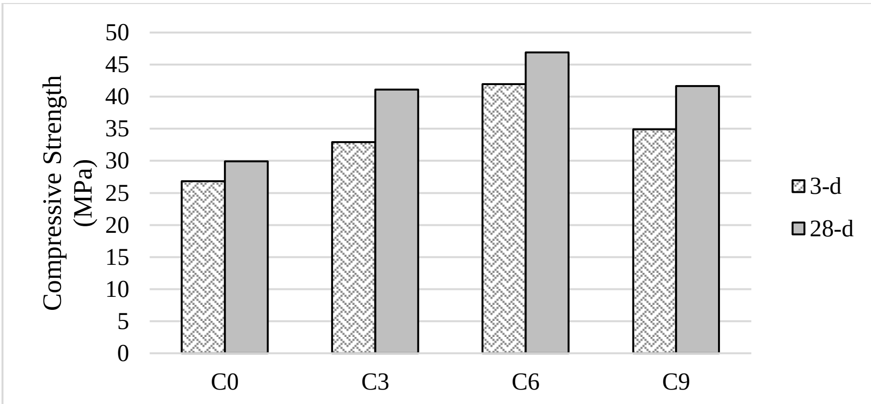

Figure 5. Compressive strength.

When 3-day concrete compressive strengths were compared, the compressive strength increased by 22.62%, 56.39 and 30.12%, respectively, compared to the reference concrete with 0.3%, 0.6% and 0.9% admixture dosages. This increase in 28-day concretes was 37.29%, 56.67 and 39.29%, respectively. The highest increase was achieved with 0.6% admixture dosage in both 3-day concretes and 28-day concretes.

The water absorption percentages were given in Table 7. The smallest value of the water absorption percentages was obtained with the use of 0.6% admixture. This means that the concrete with the least amount of harmful substances that can dissolve in water and enter the concrete is the C6 specimen, which provides an advantage in terms of durability compared to other concretes.

Table 7. Water absorption.

Concrete Code	Water Absorption (%)
C0	7.58
C3	6.78
C6	6.12
C9	6.26

The unit weights were given in Table 8. When dry unit weight values of the concretes were compared, it was seen that the dry unit weight value of C6 concrete was the highest and the volume of the voids in this concrete was the least. Dry unit weights of C3, C6 and C9 specimens were 2.51, 2.93 and 2.09% higher than the reference concrete, respectively. In saturated unit weights, these increases were 2.33%, 1.56% and 0.78%, respectively. Saturated unit weight values were affected by the void structure of the concrete, concrete mix design and the percentage of water absorption.

Table 8. Unit weights.

Concrete Code	Dry Unit Weight (g/cm^3)	Saturated Unit Weight (g/cm^3)
C0	2.39	2.57
C3	2.45	2.63
C6	2.46	2.61
C9	2.44	2.59

Ultrasonic pulse velocity and dynamic modulus of elasticity were given in Table 9.

Table 9. Ultrasonic pulse velocity and dynamic modulus of elasticity.

Concrete Code	Ultrasonic Pulse Velocity (km/s)	Dynamic Modulus of Elasticity (GPa)
C0	4.44	30.34
C3	4.60	34.74
C6	4.72	35.59
C9	4.70	35.48

When the ultrasonic pulse velocity values were examined, it was observed that the UPV value of C6 concrete was the highest. The UPV of C3, C6 and C9 specimens were 3.60%, 6.31% and 5.86% higher than the reference concrete, respectively. According to the ASTM C597 (2016) standard, if the ultrasonic pulse velocity is between 3.5 and 4.5 km/s, the concrete quality is considered as good. Accordingly, since the reference concrete met this requirement, the quality of this concrete was good, and the concrete quality has improved in the concretes produced with admixtures. In ASTM C597 (2016), the quality of the concretes with ultrasonic pulse velocity above 4.5 km/s is given as very good. As it is known, ultrasonic pulse velocity increases in specimens with less void amount. Unless a property such as low unit weight of concrete or being able to be used as an insulation material is aimed, it is desired that the amount of voids in the concrete to be low. The low amount of voids in the concrete improves the concrete properties in terms of compressive strength and durability, and increases the concrete quality.

The highest dynamic modulus of elasticity was obtained in C6 concrete. The dynamic modulus of elasticity values of C3, C6 and C9 specimens were 14.50%, 17.30% and 16.94% higher than the reference concrete, respectively. The relationships between ultrasonic pulse velocity (UPV)-28 day concrete compressive strength and UPV-dynamic modulus of elasticity were shown in Figure 6. The data obtained were affected by the void structure of the roller compacted concrete. As the amount of voids in the RCC increased, UPV decreased, and the compressive strength and dynamic modulus of elasticity (E) decreased. Although an approximate correlation can be established between the modulus of elasticity of concrete and the compressive strength, differences may occur in the modulus of elasticity due to the fact that concrete is a composite material that does not have a homogeneous structure (Turkel, 2002; Yasar et al., 2020).

There was a linear relationship between ultrasonic pulse velocity and concrete compressive strength since both values were affected by the amount of voids in the concrete. Similarly, a linear relationship was obtained between the ultrasonic pulse velocity and the dynamic modulus of elasticity.

For each chemical admixture, there is the most appropriate type of admixture to be used and a dosage range in which the admixture will work most effectively, depending on the properties and quantities of the materials used, the presence of different chemical or mineral admixtures, the characteristics of the admixture, the temperature, humidity and wind conditions during concrete pouring. Depending on the ambient conditions and the admixture content, differences in concrete properties can be observed (Bekem Kara and Arslan, 2020; Kavitha et al., 2020). When admixtures below a certain dosage are used, the admixture cannot show the effect expected, while excessive use of admixtures may cause some undesirable effects on the concrete.

It was observed that the overdose usage of lignosulfonate-based admixtures negatively affect physical and mechanical properties of concrete (Topcu and Atesin, 2016). Topcu and Atesin (2016) reported that while the lignosulfonate-based admixtures used at the optimum rate decreased the pore volume in the mortar and improved the mortar properties, the material properties were adversely affected in excessive use, and it was seen in the SEM (scanning electron microscopy) analysis results that the excessive use of admixtures caused the mortar structure to be more porous.

The most appropriate way to prevent this is to take into account the dosages recommended by the admixture manufacturer, as well as to make a preliminary production with the materials to be used and to start the main production after checking that the targeted properties of the concrete are achieved through preliminary experiments. In this experimental study, the most suitable admixture dosage was 0.6% with the materials used. Similar results were obtained in a study conducted with conventional cement mortars, and it was stated that the results obtained by performing XRD (X-ray diffraction) analysis showed that the main crystalline structure's intensity increased with an increase in the admixture dosage up to 0.5%, and decreased with an increase to 1% (Algan et al., 2022).

However, it is possible to obtain different results when a production is made with different materials under different conditions or when the concrete design is changed. The results obtained will vary depending on the void structure of the concrete produced, the bond strength between the aggregate-cement interface, and some other factors such as the physical and chemical properties of the concrete.

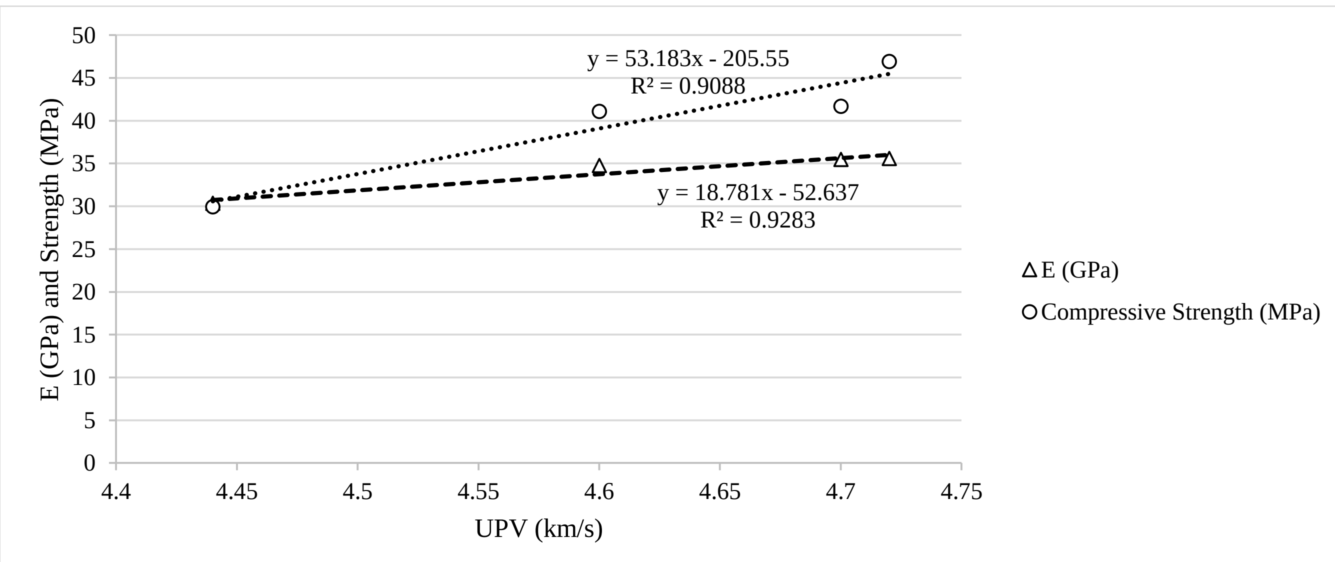

Figure 6. UPV, concrete compressive strength and dynamic modulus of elasticity.

4. Conclusions and comments

Based on the data obtained from the experimental study, the following conclusions could be drawn:

- The admixture dosage was 0.6% in the concrete where the compactibility was maximum.
- The admixture dosage was 0.6% in the concrete where the water absorption was minimum.
- Roller compacted concrete with the highest ultrasonic pulse velocity, compactness, compressive strength at the ages of 3 and 28 days, and dynamic modulus of elasticity was the concrete produced with 0.6% admixture dosage. The increases in compressive strength observed in the roller compacted concretes produced with the chemical admixture are due to the uniform distribution of the cement paste, it provides better compaction and reduces the voids in hardened concrete, thereby improves concrete compressive strength as well as other concrete properties.

- With the concrete mix design and the compaction aid chemical admixture in question, it has been observed that the optimum dosage of chemical admixture for the production of the best quality concrete in terms of the concrete properties examined was 0.6%.
- Chemical admixtures are needed to improve certain concrete properties. Concrete properties are affected by the dosage of admixtures used in roller compacted concretes, as in conventional concretes. There is an optimum dosage of admixtures to ensure the best concrete properties. When using more or less admixtures than this amount, the desired performance cannot be achieved and concrete properties are adversely affected. The amount of admixture needed may vary depending on the materials used, admixture properties and concrete mix design.

Author contributions: Saadet Gokce GOK: Designed the analysis and collected experimental data, searched for literature, analyzed the data and wrote the article. Ismail KILIC: Planned and designed the analysis and collected data.

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