Research Article

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Effect of aggregate size on the restrained shrinkage of the concrete and mortar

Abstract

Mostly, there are investigations about the shrinkage of the concrete. In that research, only the effect of the coarse aggregate on shrinkage is investigated; the fine aggregate is taken into account with the coarse aggregate. When the aggregate grain size increases or decreases, which results will be obtained and how this situation affecting the shrinkage should be determined. In this study, firstly, a widely literature research related to the effect of the aggregate grain size on the shrinkage were carried out. Then, with the help of the experimental studies, it is possible to determine the effect of the aggregate grain size on the shrinkage of the concrete and mortar whether if the aggregate grain size decreases or increases. These experimental researches are on the restrained and drying (free) shrinkage, moreover the compressive and tensile strength tests were carried out. When the effect of the aggregate grain size on the shrinkage, the shrinkage of the mortars with the 4mm maximum grain size is low if the amount of the aggregate is high. Compared to the mortars (especially maximum grain size is 9mm) the shrinkage value is lower. When the concrete with the 16mm maximum grain is produced according to the same ratios of the mortar, the shrinkage of the concrete is less than the shrinkage of the mortar. According to these results, the shrinkage decreases while the maximum grain size is bigger than 9 mm. Coarse aggregate restrains the development of the crack and supply as a micro-crack. The aggregate restrain the shrinkage if the strength of the concrete is high. The compressive and tensile strengths of the mortar and concrete are high at 28 days and decrease at 42 days because the micro-cracks reduce the strengths a little.

Keywords: restrained shrinkage, aggregate grain size, ring sample, strengths, concrete, micro-crack

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Mustafa Erkan Karagüler,[1] Mehmet Serkan Yatağan[2]

[1]Associate Professor, Dr. Istanbul Technical University, Turkey
[2]Lecturer, Dr. Istanbul Technical University, Turkey

Correspondence: Mustafa Erkan Karagüler, Associate Professor, Dr. Istanbul Technical University, Faculty of Architecture, Taşkışla Street 34437, Taksim, Istanbul, Turkey, Tel 902-122-931-3 00/2340, Fax 902-122-514-895, Email karagulerm@itu.edu.tr

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Introduction

Since the aggregate is 80% of the total volume of the concrete and mortar, the characteristic properties of the aggregate affect the fresh and hardened properties of the concrete and mortar.[1] The characteristic properties of the aggregate such as the shape, the size and structure affect the properties of the fresh concrete and the mortar like workability, settlement, pumping and segregation and the properties of the hardened concrete and the mortar like the strength, the Young's modulus, the shrinkage, the creep, the density, the permeability and the durability. The grading or the distribution of the aggregate size affects some properties of the concrete such as the density, some pores, workability, segregation and the durability. According to some researchers, the mixture with the proper distribution of the aggregate size has the appropriate workability than the mixture with the improper distribution of the aggregate size.[2] Moreover, the grading affects the properties of the hardened concrete and mortar. The mixture with the proper distribution has the high density, less permeability and high abrasion strength.[2] Consequently, the mixture with the proper distribution requires less cement paste thus less perspiration, less creep and shrinkage occur.[3,4] Aitcin[5] told that high amount of coarse aggregate decreases the free shrinkage but increases the micro-cracks in the paste. If the aggregate grain size is low or high, it causes poor workability and less durability.[4,6] The amount of the coarse and fine aggregate should be in equilibrium. For example, more sand requires more cement and viscous mixture forms, the pumping is difficult and finish and crack problems occur.[4] Additionally, perspiration and permeability increase.[1] On the other hand, less sand form lean mixtures and finish problems.[1,4] If the amount of fine aggregate is high, the perspiration, segregation, and hardening problems occur. However, if the aggregate is too much fine, the amount of the required water increases.[6] The proper sizing depends on the shape and tissue of the aggregate. The effect of the grading, the shape and the size of aggregates on the shrinkage is indirect, but it is important to determine how they affect the amount of water. On the other hand, the properties of the aggregate enrich the bond between the aggregate and the paste. For example, the surface structure, the shape, and the porosity decrease the drying (free) shrinkage.

According to one of the researchers, the increase in the diameter of the aggregate increases the width of the micro-crack at the constant amount of the aggregate.[7] The concrete shrinks due to inner and outer restraints. The internal restraint is the main property of the shrinkage and has two types; autogenous shrinkage and aggregate restraint. These two constraints occur during the external restraints. The effect of the aggregate restriction on the development of the crack depends on the quantity of the shrinkage of the paste and the ratio between the Young's modulus of the aggregate and the paste. Golterman et al.,[8] investigated the micro-crack due to the aggregate restraint and determined that the micro-cracks develop perpendicular to the boundaries of the grains because of the aggregate restraint. The degree of the free shrinkage defines the aggregate restraint. The autogenous shrinkage form the micro-cracks a little bit depth from the drying surface whereas the aggregate restraint form the micro-cracks in the mass of the concrete and the mortar. Moreover, the aggregate restraint changes according to the types of the concrete.

Especially, the effect of the size of the aggregate on the shrinkage gets importance to increase the workability of the cement-based materials. For supplying the required workability of the settlement, the more water should be added to the mixture of the concrete and the mortar. When this excess amount of water evaporates, the cement paste shrinks. The concrete and the mortar must have the maximum quantity of the hard and clean aggregate to restrain the shrinkage of the cement paste. If the dry volume of the hard and clean aggregate is equal to the volume of the concrete and the mortar, the aggregate restrains the shrinkage of the cement paste precisely. Using the biggest aggregate grain size supplies less amount of the cement paste and then decreases the shrinkage. When only the fine aggregate is used, the amount of the aggregate should be high to reduce the shrinkage. Especially, if the quantity of the fine aggregate is four times as the amount of the cement, the shrinkage in the mortar is lesser than the shrinkage in the concrete. The effect of the maximum aggregate grain size on the development of the crack is investigated with the comprehensive tests. For example, Walker & Bloem[9] determined that strength and maximum aggregate grain size are inverse ratio with the help of the comprehensive test so the bigger aggregate causes weak concrete.

The effect of the maximum aggregate grain size on the development of the crack is defined as;

1. When the crack runs into the aggregate, it travels around the aggregate on the same way. This situation forms more crack surface energy. Therefore, the crack width is little when traveling around the aggregate.
2. When the crack runs into the aggregate, it enters into the interface between the aggregate and the cement and continues in the paste. The restraint of the development of the crack depends on the toughness of the interface and the size and the shape of the aggregate grains.
3. The crack which continues in the cement paste differs from the original crack because the initial crack travels around the aggregate.

Bisschop & Mier[10] studied the effect of the aggregate on the micro-cracks of the concrete due to free shrinkage. They used the spherical glass grains instead of the natural aggregate because the spherical glass grains have the same Young's modulus and have the same restraint as the natural aggregate like quartz pebble and the sand. Also, they are easily obtained. Moreover, due to being spherical, they just supply the investigation of the size effect. The development of the crack is investigated by measuring the crack width at the two stages of the drying. The crack widths are measured with the optical and scanning electron microscope. They determined that small grains do not help the formation of the micro cracks. However, more amounts of the small grains decrease the crack widths and lengths because the amount of the aggregate which restrains the shrinkage is high. In some parts of Giaccio & Zerbino's[11] study, the effect of the coarse aggregate on the formation of the crack is investigated. They specify the effect of the coarse aggregate increases when the strength increases because they determined that when the strength of the paste is close to the strength of the aggregate, the probability of the crack development through the aggregate increases. For another result, the strength and the potential of the crack formation in the concrete with the pebble is lower than the concrete with the crushed stone. The crushes stones have a rough surface, straight angle, and high strength to restrain the shrinkage mechanically.

Sahmaran et al.,[12] investigate the effect of the aggregate grain size on the formation of the crack. In the tests, they study the impact of the aggregate at constant water/cement ratio. The variable parameter is the maximum aggregate grain size. The width of the crack is measured with the microscope and also the free shrinkage of the samples is measured. Especially, when the grain size of the fine aggregate increases, the crack width and free shrinkage decreases in the mortar. In other studies, the effect of the different conditions such as the concrete with the shrinkage reducing admixtures, fiber reinforced concrete, the specimen size on the restrained and the free shrinkage is investigated by producing the cement based materials which have different aggregate grain size. The restrained shrinkage of the cement-based material is measured with the ring specimens. In Table 1, the changes of the free and restrained shrinkage of the cement-based materials which have a different aggregate grain size in some studies are shown.

Zhang et al.,[13] clarify experimentally the influence of the aggregate materials characteristics, which are coarse aggregate shrinkage strain, specific surface area of aggregate materials, water absorption ratio and pores structure of coarse aggregate, on the drying shrinkage property of mortar and concrete specimens. Based on the experimental results, in the main findings of this study, the drying shrinkage strains in investigated mortars were changed significantly by different kinds of fine aggregate materials. While, for concrete specimens, the fine aggregates showed inconsiderable effect due to the less volume portion. The primarily affecting factors on drying shrinkage development in concrete specimen are the kind of coarse aggregate and their characteristics, such as coarse aggregate shrinkage strain, specific surface area of aggregate, absorption ratio and pore structure of coarse aggregate. The test results revealed that the smaller the coarse aggregate shrinkage strain the less is the drying shrinkage strain of concrete, which means that the coarse aggregate not only play a role in restraining the drying shrinkage of concrete, but also play a pole with regard to the drying shrinkage development of concrete. It was concluded that the concrete shrinkage can be controlled by reducing the total amount of water, and appropriate aggregate characteristics as well. Falade et al.,[14] examine the influence of plasticizers and varying the aggregate size on the drying shrinkage and compressive strength of laterised concrete. As a result of the study, the addition of super plasticizer increased the compressive strength and reduced the shrinkage strain of all specimens; while increase in coarse aggregate size reduced both compressive strength and drying shrinkage. Nakomoto et al.,[15] obtain data on the drying shrinkage of coarse aggregate available at the stockyard in ready-mixed concrete plants, and its static modulus of elasticity and its compressive strength in order to utilize the coarse aggregate as local resources efficiently. The quality of coarse aggregate is one of the crucial factors affecting the quality of concrete. The drying shrinkage of the aggregate increases the shrinkage of the concrete. The shrinkage of the aggregate is also related to the static modulus of the elasticity as well as the rate of water absorption.

Zhu et al.,[16] investigates the volume and gradation of coarse aggregate on the drying shrinkage of SCCs and compares the restrained shrinkage of the concrete and the mortar. The shrinkage behavior of the cement-based materials with only fine aggregate or both fine and coarse aggregate should be investigated and evaluated. Besides of the measurement of the restrained and drying shrinkage,

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the compressive and tensile strength of the mortar and the concrete are measured. Moreover, during free shrinkage measurements, the weight losses of the specimens are also measured. Based on the experiment results, coarser aggregate had a higher restraint coefficient, indicating better restraint on the volume deformation of mortar. Dittmer & Beushausen[17] evaluate the influence of coarse aggregate volume content and size on the individual key material properties known to affect overlay cracking, as well as testing the direct influence of coarse aggregate content and size on overlay cracking with the ring test experimentally and analytically. The experimental and analytical results reveal that at equal coarse aggregate contents, an increase in aggregate size was found to improve cracking behavior of concrete subjected to restrained shrinkage. The effect of coarse aggregate size was especially pronounced at higher aggregate contents.

Table 1 The change of the free and restrained shrinkage of the cement-based materials which have different aggregate grain size in some studies

Reference	D_{max} (mm)	The Day at when the crack forms	The crack width (mm)	Drying shrinkage (x 10^{-6})
Shah et al.[18]	9	6	0,72	540
Grzybowski[19]	9	7	0,9	1025
Sarighaputi et al.[20]	9	7	0,98	650
Wiegrink et al.[21]	9	7	0,95	810
Li et al.[22]	10	8	0,8	1200
Collins & Sanjayan[23]	14	7	0,6	500
Hossain & Weiss[24]	9	11	0,85	500
Maine et al. [25]	20	13	0,82	-
Gesoglu et al. [26]	9,5	8	2,61	1412

Materials and methods

Aggregate and cement

In this work, Adapazari river sand is used as the fine aggregate. The pressed and loose unit weights of the fine aggregate are 1618.8gr/dm^3 and 1517.6gr/dm^3 relatively. The specific weight is 2.58gr/cm^3. The water absorption of the fine aggregate is 0.9%. The maximum aggregate grain size of the fine aggregate is 4mm. The pebble is used as the coarse aggregate. The pressed and loose unit weights of the coarse aggregate are 1687gr/dm^3 and 1529 gr/dm^3 relatively. The specific weight is 2.70gr/cm^3. The maximum aggregate grain size of the coarse aggregate is 16mm. CEM I Portland cement is used. The specific weight of the cement is 3.17gr/cm^3. The beginning time of the hardening is 2 hours 28 minutes and the finish time of the hardening is 3 hours 47 minutes. The fineness of the cement is 0,2 % above 210µ, and this value of the fineness is smaller than 1% in TS EN 196-6 Cement Test Methods Chapter 6: The Fineness Method.

The mixture ratio and production

The mixture ratio of mortar is determined by investigating the other studies and is chosen as 1:4:0,5 which is the ratio of the weights of the cement, the fine aggregate (sand) and water relatively. The mixture ratio of concrete is the same as 1:4:0,5 which is the ratio of the weights of the cement, the fine and coarse aggregate (sand, pebble) and water relatively. The water/cement ratio of the mortar and concrete is constant as 0.5. In Table 2, the amount of materials in 1m^3 mortars and concrete is revealed. In the production of concrete and mortar, the aggregates are mixed with the half of the water for one minute and then the cement is added and they are mixed for one minute. After 1 minute, the rest of the water is added and mixed for 4 min. For the restrained shrinkage tests, the inner and outer diameters of ring samples are 270mm and 300mm consecutively Figure 1. Fresh mixture is settled to the 30cm width and 120cm height ring molds by pricking, and after the settlement, the molds are vibrated for one minute in Figure 2. For the free shrinkage, three prisms with 4x4x16cm dimension are produced. Another three prisms with 4x4x16 cm size are produced to measure the mechanical properties. According to AASHTO PP34-98, the ring specimens are held at 20°C and 40% relative humidity for 24 hours, and then, they are taken out from the molds. The upper parts of the ring specimens are covered with the silicone coatings in order to allow to drying from the outer, circumferential surface. The crack width is observed with the 10X special microscope in Figure 3. The measurements are made every day for 42 days to determine when the crack occurs and the development of the crack width. According to ASTM C157-98, the change in the length of the prisms is measured every day for 42 days to determine the drying (free) shrinkage. Also, the weight loss of the prisms is measured. 4x4x16cm prisms are used to measure the tensile strength on 3, 7, 28 and 42 days. After the prism is settled on the supports, they are loaded with the half of the length the specimens, and the fracture load is recorded. Broken samples in the tensile strength test are used to measure the compressive strength on 3, 7, 28 and 42 days.

Table 2 The effective amount of materials in 1m^3 concrete and mortar

Mixture	Water (kg)	Cement (kg)	River sand (kg)	Pebble (kg)
Mortar	211	428	1687	-
Concrete	225	450	860	893

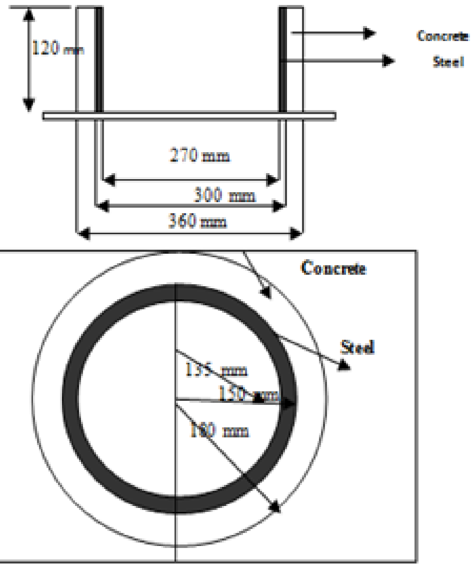

Figure 1 The ring specimens of the restrained shrinkage test.

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Figure 2 The production of the ring samples.

Figure 3 The measurement of the restrained shrinkage with 10x microscope.

Results and discussion

The restrained shrinkage

The crack forms at 12 days for the mortar and the first average crack width is measured as 0.12mm in Figure 4. At 42 days, the maximum average crack width is measured as 0.5mm. In Table 3, the change in the crack width of the mortar is shown. In Figure 5, the graphical change is also revealed. The first crack forms in the concrete at 10 days and the first average crack width is measured as 0.05mm. At 42 days, the maximum average crack width is measured as 0.4mm. This situation is revealed in Table 4 & Figure 6. Although the crack forms in both mortar and concrete at an approximately same time, the crack width of the concrete is smaller than the mortar.

Figure 4 The cracks of the restrained shrinkage.

Table 3 The average crack width of the mortar

Day	Crack width (mm)			Average crack width (mm)
	1	2	3	
11	0	0	0	0
12	0,1	0,1	0,17	0,12
13	0,17	0,1	0,17	0,15
14	0,23	0,1	0,17	0,17
20	0,27	0,1	0,27	0,21
22	0,3	0,2	0,27	0,26
24	0,33	0,23	0,3	0,29
27	0,4	0,23	0,37	0,33
28	0,4	0,3	0,37	0,36
30	0,5	0,33	0,4	0,41
34	0,5	0,37	0,4	0,42
35	0,5	0,37	0,4	0,42
36	0,53	0,43	0,47	0,48
37	0,53	0,43	0,47	0,48
38	0,53	0,43	0,47	0,48
42	0,53	0,5	0,47	0,5

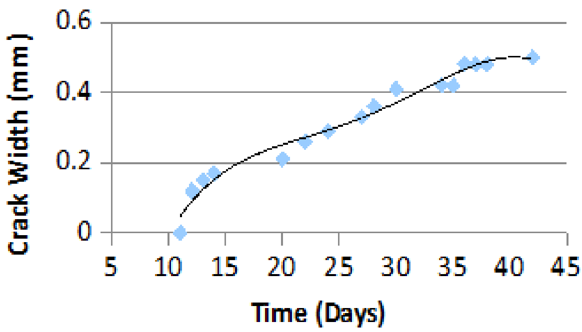

Figure 5 The Crack width change in the restrained shrinkage of the mortar.

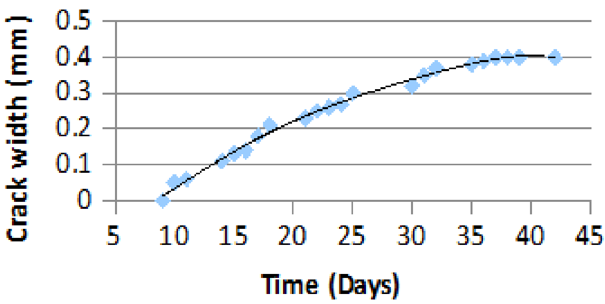

Figure 6 The crack width change in the restrained shrinkage of the concrete.

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Table 4 The average crack width of the concrete

Day	Crack width (mm)			Average crack width (mm)
	1	2	3	
9-Jan	0	0	0	0
10	0,05	0,05	0,05	0,05
13	0,12	0,2	0,12	0,12
14	0,13	0,13	0,13	0,13
20	0,22	0,22	0,22	0,22
22	0,23	0,23	0,23	0,23
24	0,25	0,25	0,25	0,25
25	0,3	0,3	0,3	0,3
28	0,31	0,31	0,31	0,31
30	0,32	0,32	0,32	0,32
34	0,35	0,35	0,35	0,35
35	0,38	0,38	0,38	0,38
36	0,4	0,4	0,4	0,4
37	0,4	0,4	0,4	0,4
38	0,4	0,4	0,4	0,4
42	0,4	0,4	0,4	0,4

Free shrinkage and weight loss

The change in the length Figure 7 and weight of the specimens is measured for 42 days. The drying shrinkage is calculated by dividing the change in the length to the first length. The drying shrinkages of the mortar and the concrete are 812.5x10-6 and 687.5x10-6 relatively. Like the restrained shrinkage, the free shrinkage of the concrete is smaller than the mortar. When the weight loss is compared, the percentage of weight losses of the mortar and concrete are 4.18% and 2.85 relatively. The same result is obtained like the restrained and free shrinkages. The change of free shrinkage and weight loss of mortar and concrete is demonstrated in Figures 8 & 9.

Figure 7 The Measurement of the free shrinkage.

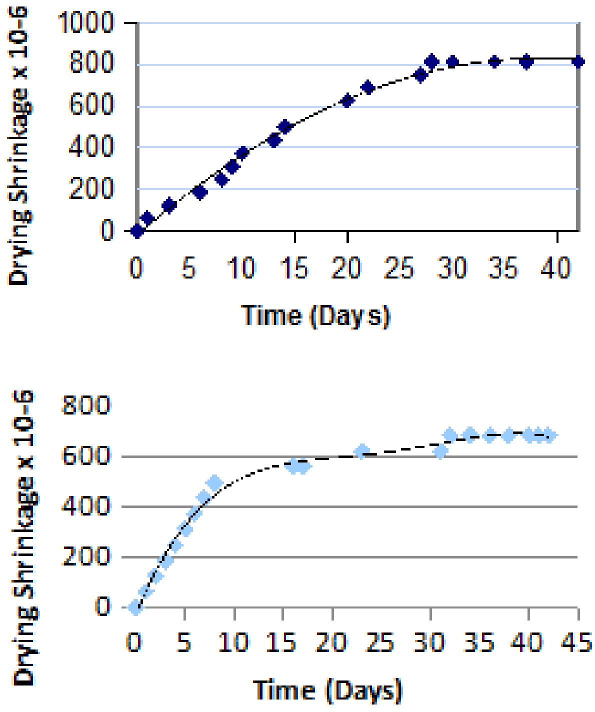

Figure 8 The change in the free shrinkage of the mortar and concrete.

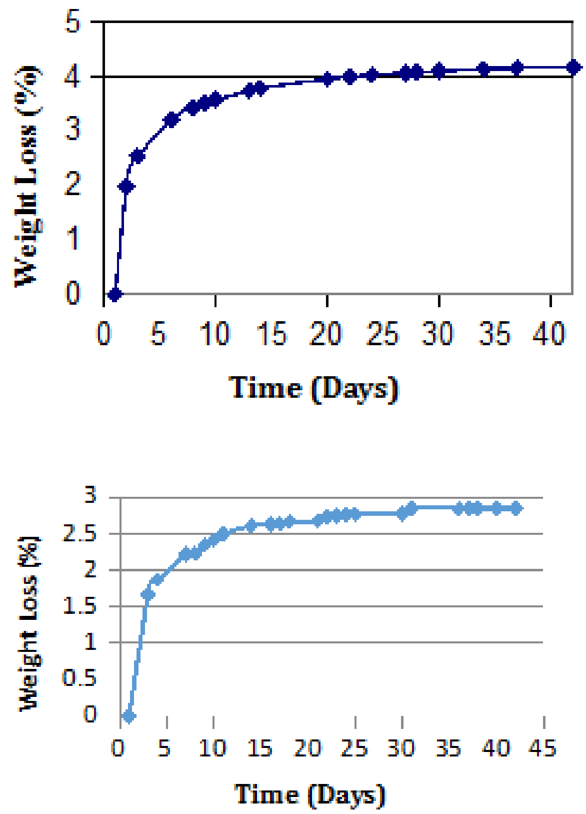

Figure 9 The change in the weight loss of the mortar and concrete.

The compressive and tensile strength

The compressive and tensile strengths of the mortar and concrete Figure 10 are highest at 28. days whereas the compressive and tensile strengths decrease a little bit at 42 days Table 5. As a result of this situation, when the shrinkage becomes constant, the forming micro-cracks reduce the strength a little bit.

Figure 10 The Measurement of the compressive and tensile strengths.

Table 5 The compressive and tensile strengths of the mortar and concrete

The compressive strength (N/mm²)					Tensile strength (N/mm²)			
Days	3	7	28	42	3	7	28	42
Mortar	31,2	36,8	40,3	38,2	3,7	5,5	7,61	7,19
Concrete	37	38	41	38	5,16	6,02	6,17	6,15

Conclusion

Mostly, there are investigations on the drying (free) and restrained shrinkage of the concrete. In these investigations, only the effect of the coarse aggregate on free shrinkage is investigated and the size and the amount of fine aggregate are neglected for the restrained shrinkage. If the effect of the fine aggregate on the restrained shrinkage is investigated, it is possible to determine the effect and behavior of the aggregate grain size. Also, the results are compared with the investigations about the effect of the coarse aggregate. In this study, within the help of the experimental researches on restrained shrinkage, it is possible to determine the effect of the aggregate grain size on the restrained shrinkage of the concrete and mortar:

1. When the effect of the aggregate grain size on the restrained shrinkage is investigated, the restrained shrinkage of the mortar with 4mm maximum aggregate grain size and with high amount of the aggregate is small and also; it is lower than those of the concrete with 9mm maximum aggregate grain size. However, when the concrete is produced with the same ratios of the mortar with 4mm maximum aggregate grain size, the restrained shrinkage of the concrete which has 16mm aggregate grain size is smaller than that of the mortar.
2. According to these results, when the maximum aggregate grain size is equal or bigger than 9mm, the shrinkage decreases. The larger grains restrain the inner strains and prevent the change of the micro-cracks to the macro-cracks.
3. When the high amount of fine aggregate is only used, the shrinkage of the mortar is close to that of concrete with the bigger aggregate grain size. Also, the compressive and tensile strengths of the mortar and concrete are highest at 28 days whereas the compressive and tensile strengths decrease at 42 days. As a result of this situation, when the shrinkage becomes constant, the formation of micro-cracks reduces the strength to a certain degree.
4. As a result of the study, the increasing aggregate grain size restrains the shrinkage cracks as the micro cracks before becoming as the macro cracks. This is a major concern for flat structures, such as pavements, parking lots and highway bridges, because of the corrosion problems.

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Conflicts of interest

The author declared that there are no conflicts of interest.

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