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Investigating the Effect of Cement Grading on the Characteristics of Concrete and Standard Mortar

Ali Akbar Kafash Bazari [1*], Zivar Nikfal [2], Mohamad Vatani [3]

[1] Chief of research and development of Tehran cement Co, Tehran, Iran.
[2] Chief of physical Laboratory of Tehran cement Co, Tehran, Iran.
[3] Expert of Tehran Cement Quality Control Laboratory.

*Correspondence should be addressed to Ali Akbar Kafash Bazari, Chief of research and development of Tehran cement Co, Tehran, Iran. Tel: +982133421231; Fax: +982133421231; Email: Kafash@Tehrancement.co.ir.

ABSTRACT

Grading is one of the most important characteristics of cement, which has a great impact on its performance in concrete. The most common methods of monitoring are determination of residues on sieves, Blaine and LD. In this study, introduce the main parameters of cement grading, optimal limits and its effects. Also 204 samples of Portland cement were prepared to determine their physical and mechanical properties and performance of Laboratory concrete mixtures. One of the most important results is the clear effect of increasing the share of 3 - 30 µ particles and cement uniformity coefficient on the compressive strength of concrete and mortar and providing relationships. The results of LD- PSD experiments were well correlated with the experiments remaining on the sieve by alpine method. With increasing uniformity or the amount of particles of 3 - 30 microns, the setting time of cement paste increases (becomes longer); which is not always desirable.

Keywords: grading, PSD, cement, Mortar, concrete.

1. INTRODUCTION

In order to improve the efficiency of cement and its properties, the effects of cement particle size distribution (PSD) on the hydration process should be considered, and various sources have emphasized the importance of this issue [1-6]. The sieving method [8-7] is not very desirable for cement powder and is the only standard method for measuring PSD cement (turbidimeter or Wagner test) in terms of limited amplitude (smaller than 7.5 microns) [9]. Because there is no standard method that covers a wide range of cement PSDs, the measurement methods in the industry are very different. It is emphasized that the combination of the results of tests to determine the fineness of cement (Blaine) [10], residues on 45 and 90-micron sieves, and laser grading is the best option to control the quality of cement wear. It is interesting to note that in forensic medicine, the PSD of very small specimens needs to be accurately determined using a fast and reliable high-resolution method [11]. Laser grading is of special importance in the cement industry, so in the laboratory operations of this paper, we tried to observe the compressive strength of standard mortar and concrete using this method. First, the main characteristics of laser cement grading and its limits are introduced. Particle size between 3 to 30 microns (Δ3-30): 1-For cement with normal mortar strength: 40-50%; 2- For high strength mortar cement: 55-65%; 3- For cement with very high mortar strength: above 70% has been introduced [12], some other authorities have mentioned at least 50% of this index [13]. According to experimental studies, when the particle size of 3-32 microns in the Portland cement sample increases to 42.5 R, a 13% improvement in 28-day compressive strength is achieved (Figure 1). By decreasing the specific surface area of the cement (Blaine value) and increasing the fraction by 5-20 microns, the initial strength increases due to the improved homogeneity of the particle distribution [14].

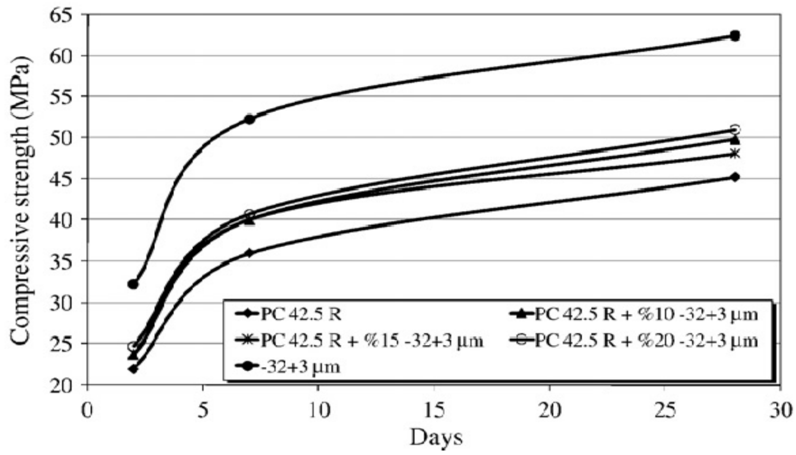


Figure1. Comparison of compressive strength of 32-32 micron cement fraction of 42.5R with samples with different grading [14]

The fineness parameter (d') is the sieve index under which 63.2% of the particles are located. If cement's uniformity coefficient (n) is less than 0.9, it indicates a wide and undesirable particle distribution curve, but a uniformity coefficient greater than 0.9 indicates a narrow distribution [15]. The uniformity coefficient is expected to be about 1.2-1.1 in the roller mills and 0.9-0.1 in the bullet mills. In principle, increasing the uniformity coefficient is a positive factor in improving grading, which leads to improved cement strength. It should be noted that operations to achieve large particle size distributions have costs (operating and energy consumption measures) [16]. Increasing the fineness of cement (Blaine) is not always desirable because increasing the fineness of cement increases the need for water consumption (demand) of concrete, and usually, to obtain the smoothness of concrete, the w/c ratio increases, which ultimately increases the strength of concrete despite increasing mortar strength. Does not result [17]. Cement with a narrower grain size curve (less particle size variation) or cement with a higher Blaine (more fineness) has shown the greatest demand. Of course, more water demand in cement also leads to longer setting times [18]. On the other hand, it should be noted that grinding any material that contains two or more different components (in terms of abrasion) (such as clinker, gypsum, pozzolan, lime, and slag in cement) leads to the distribution of two- or multi-phase grading [19]. ASTM Committee C01.25.01 has supported a new method for measuring the PSD of cement [20]. The results of statistical analysis of the collected data on cement pastes produced from the combination of fine cement (SFC) with ordinary Portland cement (OPC) have shown that the PSD of cement paste mixed with SFC is closer to the optimal PSD. The results of bulk density, flow ability, rheology, and strength performance of cement paste mixtures have also shown the improvement of SFC application properties, which brings PSD in cement paste closer to the desired level [21]. Based on the studies of Ferraris et al. (2004), no clear relationship was observed between the measurement time in the new experimental method and the PSD results [22]. Mitrovic (2004) worked on dry and wet grading methods and stated that the PSA 1090 method is an excellent system for combining liquid and dry measurements and cement particle analysis [23]. Frigione & Marra (1976) studied the relationships between PSD, specific surface area, and compressive strength in Portland cement. They showed that when the granulometric range decreases, the volume of the hydrated product increases, resulting in compressive strength. Experimental data have shown that contrary to this hypothesis, the depth of hydration depends more on the size of the particles. However, they proved that in practice, the width of the granulometric range could be minimized, and the mechanical strength of Portland cement in both mortar and concrete could be maximized [24]. According to the studies of Kuhlmann et al. (1985), the specific surface area of cement can be calculated from PSD parameters. The higher the slope of the grading curve, the narrower the distribution, which leads to an increase in cement strength [25]. Osbaeck and Johansen (1985) studied the PSD and the rate of development of Portland cement strength. According to them, the fineness of Portland cement is a key factor in determining the characteristics of its strength development [26]. Aiqin et al. (1997) investigated the effect of PSD on cement properties and found that PSD affects porosity and hydration rate; also, the ratio between components mainly depends on bulk density [27]. Aiqin et al. (1999) analyzed the effect of PSD on cement systems on cement properties. They suggested for optimal distribution of cement particles: 1-Wider PSD is useful for increasing bulk density and decreasing water absorption; 2-Thinner PSD is effective in increasing the rate of hydration; 3-In the same water-to-cement ratio, a narrow distribution is useful to reduce the porosity of the cement. In a more practical sense, PSD is optimal when n is equal to 1 [28]. Bentz et al. (1999) The effects of PSD cement on the functional properties of cementitious materials (including setting time, heat dissipation, porosity, permeability, chemical shrinkage, internal shrinkage, internal relative humidity evolution, and surface transfer microstructure) through computer simulation and several studies Experimental study [29]. Bentz et al. (2001) studied the effect of PSD on cement on initial stressors and initial autogenously Strains in cement pastes with the same water-to-cement ratios for cement with four different finenesses. These researchers used chemical shrinkage to determine the degree of hydration and the development of internal relative humidity; autogenously, deformation and development of specific stress were investigated using a sensor. Their results showed that a small autogenously expansion (probably due to the formation of ettringite) might occur and that cracking at younger ages may be avoided by using coarser cement [30]. Stark and Müller (2003) examined PSD cement and additives. According to them, particle size changes due to the reaction between water and cement in the early hydration period can be observed on site. Although not all the measured effects are clear, the change in PSD and the increase in mean particle size are consistent with the fact that the size of the hydration products is larger than the particle size of the original cement [31]. PSD, uniformity of distribution, and specific surface area (SSA) of cement have a great impact on its properties, especially strength. Accordingly, Celik (2009) conducted studies on the effects of physical parameters on the development of PC 42.5 R cement strength. In order to understand the importance of different particle size ranges in a grain size distribution, he prepared samples with different distributions, including 10, 20, 30, 45, 32-3, and 5-20 microns. According to the results of this PSD researcher, uniformity of distribution and specific surface area (SSA) is very important for the development of cement strength [32]. Binici et al. (2007) investigated the effect of PSD on the properties of mixed cement containing granulated blast furnace slag (GGBFS) and natural pozzolan (NP). They found that samples with cement and additive wear separately were relatively smaller than simultaneous wear samples and had higher compressive and sulfate strengths. Larger separate wear samples had the lowest hydration heat, and smaller separate wear samples had the highest compressive and sulfate resistance. [33]. Hwang et al. (2005) studied the effect of PSD slag cement on its rheological properties and presented similar results [34]. Hassani and Manvarian (2013) designed and optimized the non-uniform granulation of oil well cement in order to achieve the desired properties of cement slurry and stone [35]. Changoi and Zhouhi (2012) proposed a model to simulate the effects of PSD on the cement hydration process [36]. Ferraris & Garboczi (2013) identified and compared improved standard experiments to measure cement particle size and surface area. The two researchers subjected more than 30 cement samples to Blaine tests, Laser Diffraction (LD) measurement, and residue determination on 45-micron sieves and BET. According to their results, it was difficult to establish the correlation between Blaine, LD-PSD, and compressive strength in cement; however, when the cement properties were investigated, they observed a clear correlation between 28-day strength, setting time, and softness [37]. Ghiyasvand et al. (2014) investigated the effect of the milling method and PSD on the properties of Portland-Pozzolan cement. This paper describes the effect of the production method (simultaneous or separate wear) and PSD on the properties of Portland-pozzolanic (PPC) cement. The results of this study showed that the PPC particle size distribution was different for each production method, and the physical properties of cement resulting from simultaneous wear were slightly better than separate wear [38]. Arvantini et al. (2015) studied the PSD, surface area, and shape of cementitious additives (SCMs), including fly ash, grading blast furnace slag, and silica fume, in different ways. They made recommendations for SCM testing using air permeability, sieving, laser diffraction, BET, image analysis, and MIP [39]. Zhang et al. (2017) studied the preparation and application of finely ground cement in cementitious base materials. Their results showed that by adding surface modifiers and MGM, the efficiency of GC preparation could be improved, and the hydration process could be controlled at an early age. Partial replacement of PC with GC, with an optimal dose of 20% GC, can clearly increase the cement performance, resulting in an obvious increase in compressive strength. The degree of hydration, pore structure, and microstructure in ITZ can be improved in the presence of GC compared to a single PC system [40]. Wu et al. (2018) investigated the effects of PSD on the strength-filling properties of cement paste. The CPB resistance parameter model was constructed under the influence of both PSD and finite pressure based on the Mohr-Coulomb criterion. The results of this study showed the effect of optimal PSD on CPB resistance [41]. Kim (2018) investigated the effect of cement granulation on concrete strength development. According to the results of this study: A. The average diameter of cement particles increases with increasing FMC to maintain slump and air; B. With increasing FMC, the setting time is slightly delayed, which is a delay of about 0.42 hours for every 0.1 increase in FMC; C- Formula for estimating compressive strength using FMC and age with high correlation (0.942) as;

$$f_{cu}=11.177\times\log D-11.365\times FMC+25.146$$

Is where f_{cu} is the compressive strength, FMC is the fineness of the cement and D is the age of the specimen in terms of days [42]. The depth of hydration of cement particles with different sizes is different, which reflects the hydration process. Therefore, knowing and controlling the hydration depth improves the quality of cement materials' quality. Zhang et al. (2021) investigated this issue. They proposed a combined method of electron and stereological images to describe the depth of hydration of cement particles of different sizes in hardened cement materials and measured the depth of hydration of cement particles in hardened cement paste with a water-to-cement ratio of 0.35 at the age of 28 days. They did The results of these researchers showed that cement particles below 2 microns are fully hydrated, and the depth of hydration of cement particles below 10 microns is about 2 microns. This method has good accuracy for cement particles smaller than 16 microns [43]. Younees et al. (2022) investigated the contribution of PSD indices and the shape of cementitious particles in the development of viscosity models of thick suspensions. According to the results of these researchers, kE coefficient and intrinsic viscosity (η) were in good agreement with particle size indices, including the smoothness index (SSA × Gs) and particle size ratio (d502/SSA) [44]. Considering that more than one-third of electricity consumption in cement factories is consumed in the grinding process in cement mills and grading has a major role in the quality and quantity of cement, Farhadi (2007) is the best granulation range for cement and increased production and optimization of electricity consumption in Studied cement mills. Using laboratory methods, he showed the role of abrasive aid in correcting grading and, after injecting this material in the cement mill, introduced granulation in cement, increased production, and reduced electricity consumption by about 6 kWh per ton of cement [45]. The Rosin-Ramler-Benuet equation shows the effect of PSD on water absorption, degree of hydration, bulk density, and porosity. Accordingly, the effect of PSD on cement properties under different conditions is analyzed [46]. Behfar and Davarfar (1398) designed a laboratory operation to prepare a cement sample with appropriate granulation distribution by abrasion to study the behavior and properties of cement. Then they performed the industrial experiment and its effect on the strength of mortar and concrete. They showed that this sample has better conditions in terms of strength and rheology and can increase the softness and improve the grading distribution by removing very large and very fine particles, the effect of hydration reaction along with increasing concrete efficiency in water and reducing the cost of Cement mills improve [47]. As seen, many studies show that there is not enough information on the effect of cement grading changes on ready-mixed industrial concrete. Therefore, the purpose of this study is to provide some necessary information for cement and concrete producers in the field of optimal selection of cement in concrete. Therefore, specifically, the effect of cement grading changes on the technical characteristics of fresh and hardened concrete (without additives) was investigated in common experiments; So that the working method and details were similar to what often happens in reality in the industry. For this purpose, concrete mixtures with the constant flow (slump) were prepared.

2. MATERIALS AND METHODS

In the first step, 204 samples of Portland cement type 2 were prepared from 6 different cement mills. Then, physical and mechanical properties, including determination of residue on sieves, fineness (Blaine), setting time, and compressive strength of standard mortar of cement samples, were measured (Figure 2).

Figure 2. Laboratory cementation and determination of their physical and mechanical characteristics

In the next step, 204 concrete mixtures with cement samples were prepared with the aim of achieving a slump of 8 ± 0.5 cm. Figure 3 and Table 2 show the characteristics of aggregates used in this study.

Table 1. Technical specifications of materials used in concrete mix designs

Passing percent of sieve 200	Fracture (%)	ρ (SSD)	Water absorption (%)	fineness modulus (FM)	MSA	Type
0.5	45	2.57	1.50	7.2	25	gravel
4.4	*	2.53	3.39	7.0	*	sand

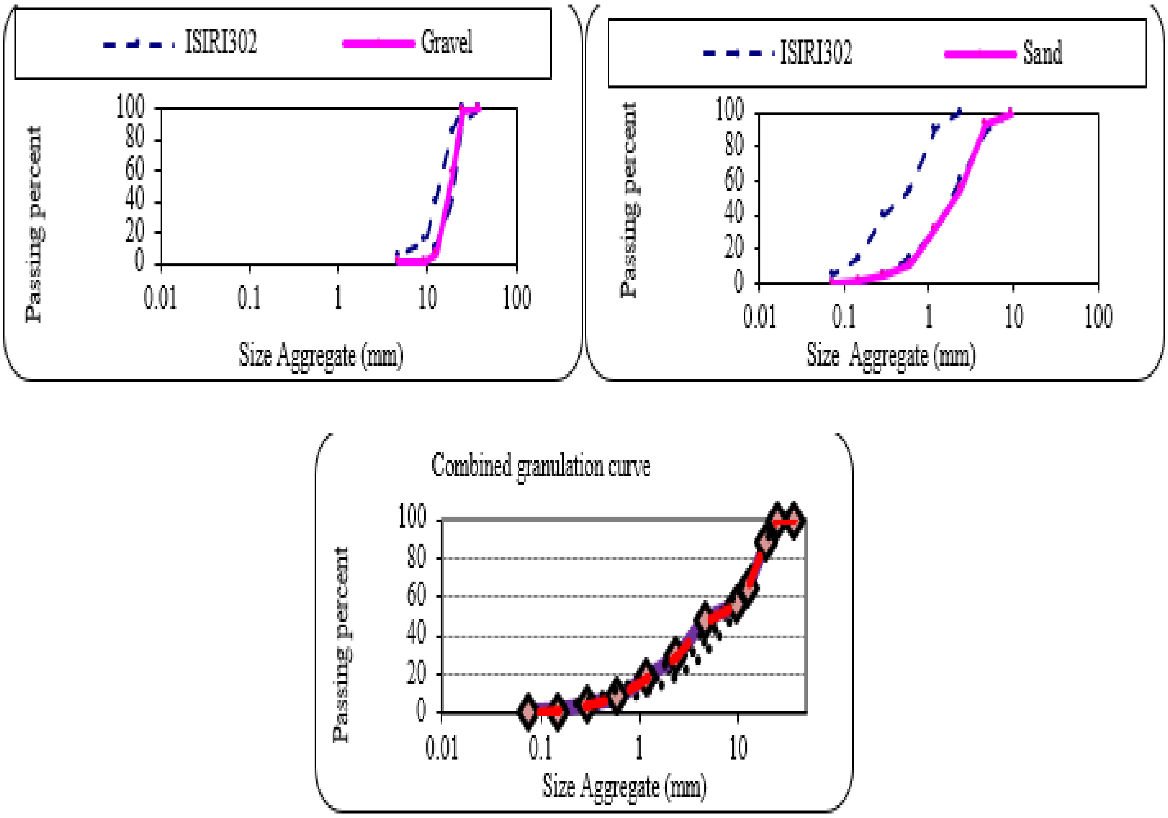


Figure 3. Particle size of sand (right), sand (left) and composition of materials (bottom) used in concrete mixes

In all mixtures, the quality of aggregates and water, weight values of materials, and physical conditions such as temperature, tools used, testers, and processing conditions have been as constant as possible so that the only variable of cement consumption is created under the same conditions (Figure 2). The grade of cement used in all designs was 350 kg/m3. Mixtures were designed nationally [48]. To prepare this mixture, 65% sand with 35% coarse sand was used (Figure 3). The compressive strength of concrete mixes was measured at 7 and 28 days (Figure 4).

Figure 4. Preparation of concrete mixes and related tests

3. RESULTS AND DISCUSSION

Table 2 summarizes the results of the experiments performed.

Table 2. Summary of test results

Comp. Strength (MPa) Concrete		w/c		Comp. Strength (MPa) Mortar		Setting time (min)		Blaine (m2/kg)	Retained on sieve (%)			Laser Diffraction	d´		n	Retained on sieve (%) LD		Code
		28days	7 days	28days	7 days	Final	Initial		30μ	45μ	90μ	3-30μ			30μ	45μ	90μ	
32/1	23/8	0/54	56/4	40/4	260	180	302	21	14	2	59	10	25	1/09	31	13	1	1
36/0	27/8	0/55	54/3	40/9	265	185	305	17	10	1	64	11	23	1/10	26	10	0	2
26/5	21/7	0/56	53/2	40/8	230	160	315	19	11	1	62	10	24	1/10	28	11	0	3
29/6	20/5	0/56	54/2	36/8	250	175	295	22	14	3	65	10	22	1/14	25	8	0	4
27/5	21/5	0/54	42/0	19/7	240	170	292	45	28	6	49	10	32	0/97	51	25	6	5
22/1	18/6	0/54	45/4	36/0	200	140	348	30	20	3	56	11	26	0/98	33	17	1	6
29/0	24/3	0/51	41/5	31/8	190	130	346	32	19	3	55	11	27	0/96	34	18	3	7
23/3	19/4	0/55	52/2	39/8	260	190	318	25	15	3	60	10	25	1/04	30	15	3	8
30/1	24/2	0/55	51/7	40/6	245	170	299	23	15	3	61	10	24	1/09	29	13	1	9
25/2	19/2	0/54	47/8	33/5	250	155	302	21	12	1	56	17	21/90	0/91	27	13	1	10
29/0	26/8	0/56	55/2	37/1	245	165	302	17	9	1	62	16	20/50	0/99	22	9	0	11
29/6	24/4	0/53	56/7	38/1	255	170	288	16	8	2	61	16	20/70	0/97	23	10	1	12
29/5	24/5	0/54	49/5	37/1	240	160	299	20	11	1	55	16	23/30	0/91	29	15	2	13
27/1	20/6	0/52	49/6	36/7	250	165	281	20	12	1	56	17	22/50	0/92	28	14	1	14
29/7	26/7	0/55	58/4	44/2	280	185	309	27	7	2	58	16	21/74	0/94	26	12	2	15
32/1	22/4	0/55	56/9	41/0	275	180	302	26	7	0	55	18	21/56	0/88	26	14	2	16
33/5	25/6	0/55	48/6	36/9	300	190	274	25	14	4	60	15	21/30	0/97	25	10	1	17
30/2	24/7	0/55	54/2	40/5	295	205	302	19	9	2	59	16	21/56	0/95	25	11	1	18
28/1	24/4	0/53	53/4	39/4	285	180	288	18	9	2	62	14	21/48	1/01	24	10	1	19
26/7	22/8	0/53	56/8	38/3	280	185	299	18	9	2	58	17	21/14	0/92	25	11	1	20
31/4	23/9	0/54	54/3	43/4	295	195	305	18	8	0	60	17	20/62	0/94	24	9	0	21
31/7	26/1	0/53	53/2	38/8	295	190	312	20	9	0	60	16	21/28	0/96	25	10	1	22
34/1	24/5	0/54	58/1	37/3	250	180	299	21	11	2	57	17	21/17	0/91	26	11	0	23
29/4	25/6	0/52	53/3	37/4	295	200	299	17	9	2	60	16	21/04	0/96	24	10	0	24
30/2	26/8	0/53	54/2	35/7	280	190	302	15	8	2	60	17	20/56	0/94	23	9	1	25
24/3	17/3	0/51	42/2	38/4	285	170	302	30	16	3	50	16	25/44	0/86	33	17	2	26
25/7	17/3	0/55	53/7	33/5	310	235	305	37	25	4	45	18	28/83	0/72	36	25	10	27
28/4	23/5	0/53	47/1	30/7	285	210	321	33	20	5	50	17	25/44	0/83	33	19	3	28
28/0	19/3	0/53	39/5	26/7	345	265	274	20	12	3	56	15	24/60	0/90	29	16	6	29
29/5	21/6	0/53	51/7	34/7	320	250	312	21	12	3	54	16	24/91	0/85	30	17	7	30
30/5	24/4	0/53	49/3	31/0	285	215	302	20	10	1	60	16	21/00	0/96	24	9	0	31
27/5	20/6	0/54	45/8	32/7	270	185	302	33	19	5	49	19	26/14	0/79	32	19	4	32
27/9	23/5	0/52	48/2	34/0	250	165	299	23	16	3	58	20	23/39	0/81	22	15	2	33
26/6	17/4	0/54	38/4	32/8	290	210	281	21	12	3	45	13	35/02	0/80	42	29	13	34
26/9	18/7	0/54	47/2	34/2	270	190	305	13	4	3	55	17	23/54	0/88	28	14	2	35
28/4	24/9	0/55	45/4	33/6	295	190	302	20	12	1	55	17	22/62	0/88	27	14	1	36
24/0	16/1	0/55	44/7	32/1	270	200	331	32	22	8	47	20	26/89	0/73	34	22	7	37
31/1	25/6	0/60	53/6	35/7	290	205	309	19	9	2	60	16	21/70	0/94	24	10	1	38
30/9	25/6	0/55	49/6	34/6	295	210	302	19	9	2	58	16	22/93	0/93	26	12	2	39
29/1	23/5	0/55	53/7	37/9	280	195	315	33	20	4	47	18	28/71	0/80	35	21	5	40
31/3	27/0	0/55	58/3	38/0	275	195	302	30	19	4	49	17	27/82	0/84	34	19	3	41
31/5	29/4	0/54	48/5	39/4	270	190	295	18	9	1	55	17	23/42	0/90	28	14	2	42
29/8	25/0	0/56	47/8	34/2	260	170	377	26	21	6	46	22	24/92	0/67	32	22	9	43
28/2	27/4	0/53	50/6	36/6	275	180	312	28	17	3	51	17	26/42	0/84	32	17	2	44
32/1	27/6	0/55	53/0	41/9	285	195	312	22	7	2	59	16	22/57	0/94	25	11	1	45
30/5	22/4	0/55	59/2	40/4	280	190	295	30	15	1	53	16	25/83	0/88	31	17	3	46
29/2	25/2	0/56	48/5	29/6	150	100	318	30	20	5	47	20	26/08	0/71	33	22	9	47
23/6	22/3	0/54	49/5	35/0	245	155	328	27	16	3	50	18	26/31	0/83	32	17	2	48
30/1	22/5	0/55	49/1	37/6	260	165	318	20	10	2	59	16	22/94	0/95	26	11	1	49
32/3	26/1	0/54	53/2	37/5	270	165	309	18	10	1	57	16	23/65	0/88	28	14	5	50
30/3	23/9	0/56	45/1	27/9	270	175	288	23	12	0	55	16	24/42	0/91	29	14	1	51
24/9	18/4	0/54	40/5	29/6	215	140	328	23	17	3	50	17	27/04	0/86	32	17	2	52
28/6	24/9	0/54	44/0	32/6	270	185	328	28	18	3	50	16	28/54	0/88	35	19	3	53
31/8	25/0	0/54	50/1	36/3	295	200	305	17	9	2	59	14	24/47	1/01	27	11	1	54
30/7	27/1	0/53	51/0	33/2	285	205	318	17	9	2	59	15	23/68	0/98	26	11	1	55
28/1	26/7	0/54	50/1	35/2	270	195	295	20	10	0	55	15	25/79	0/95	30	14	2	56
29/8	26/4	0/56	48/2	32/4	205	145	331	29	22	4	47	16	30/27	0/83	37	23	7	57
26/3	24/5	0/54	46/3	35/8	230	155	352	30	27	3	44	17	31/34	0/80	38	24	6	58
29/8	22/7	0/54	48/7	34/6	255	175	340	17	12	1	58	15	24/09	0/96	27	11	1	59
30/7	28/4	0/55	47/9	35/4	240	165	321	21	13	2	56	15	25/34	0/96	29	13	2	60
28/9	25/4	0/55	48/2	35/6	220	150	321	19	11	0	55	15	25/38	0/96	30	14	1	61
30/4	28/1	0/53	49/7	41/7	250	170	321	29	21	3	45	17	31/46	0/81	38	24	6	62
27/3	23/4	0/54	57/9	42/0	270	190	305	17	8	1	55	15	25/59	0/95	30	14	3	63
28/8	24/8	0/53	53/2	39/0	275	195	309	19	10	1	57	15	24/62	0/96	28	13	2	64
29/9	27/6	0/54	49/4	36/3	260	185	302	19	11	1	53	15	27/22	0/94	32	16	2	65
30/6	26/2	0/52	46/4	32/5	250	170	288	31	19	3	50	18	26/37	0/80	32	19	5	66
28/4	24/5	0/53	48/2	34/3	260	180	295	27	14	3	47	16	29/91	0/84	37	21	4	67
32/1	25/8	0/54	51/2	38/0	270	190	292	17	8	2	58	15	23/54	0/96	26	11	1	68
31/0	25/4	0/54	49/5	38/5	265	185	288	18	9	2	57	16	24/27	0/95	28	12	2	69
25/1	24/4	0/53	49/0	39/1	280	195	292	21	10	1	56	15	24/95	0/94	29	13	0	70
27/5	24/4	0/56	47/4	33/7	270	200	295	25	16	4	54	15	25/85	0/91	31	17	4	71
28/1	22/6	0/54	47/9	33/9	280	215	295	29	18	3	46	15	31/64	0/84	39	24	6	72
28/1	21/7	0/54	45/2	24/7	320	245	259	32	22	9	50	20	23/06	0/70	30	21	11	73
28/6	24/5	0/54	50/0	34/5	240	185	288	19	9	2	55	14	25/98	0/96	31	15	2	74
25/6	21/6	0/53	42/5	34/8	250	170	312	27	18	5	52	20	22/90	0/79	28	16	2	75
27/3	20/6	0/53	41/5	31/5	225	180	328	32	20	3	47	19	27/34	0/75	34	22	7	76
30/2	23/4	0/52	50/5	36/4	270	195	305	20	8	2	59	15	23/39	0/98	26	11	1	77
29/4	22/8	0/53	57/7	44/9	265	190	302	22	10	2	59	16	22/62	0/94	25	11	1	78
29/6	26/5	0/56	45/1	41/2	230	150	277	30	19	3	45	19	28/89	0/75	36	22	6	79
28/0	22/4	0/57	52/7	43/5	285	205	281	19	8	2	59	16	22/35	0/94	25	10	1	80
28/5	22/7	0/57	54/6	39/3	275	200	285	19	8	2	58	17	21/93	0/91	24	10	1	81
28/9	25/2	0/54	48/5	38/4	250	170	285	27	15	2	53	21	21/67	0/80	26	13	1	82
28/0	23/0	0/54	51/3	38/0	260	180	288	19	8	1	59	16	22/71	0/96	25	10	1	83
27/9	24/2	0/54	48/4	38/0	265	195	281	21	11	2	57	17	22/85	0/90	26	12	1	84
28/0	23/3	0/53	54/4	38/0	270	200	309	20	8	0	58	18	21/52	0/90	24	10	0	85
29/2	23/1	0/57	52/0	36/1	270	195	285	23	11	2	57	17	22/73	0/89	26	12	1	86
30/7	25/3	0/56	56/7	37/4	285	210	289	20	11	3	57	17	22/85	0/91	26	11	1	87
31/1	24/6	0/57	45/1	35/2	255	180	281	26	19	5	50	20	24/48	0/78	30	16	2	88
28/2	23/6	0/57	57/0	42/6	280	200	281	21	9	0	55	18	23/16	0/88	27	12	1	89
29/2	24/1	0/54	48/7	37/6	270	200	295	23	15	2	55	17	23/67	0/89	28	14	2	90
28/4	21/1	0/55	50/2	43/2	265	185	321	28	20	2	49	21	24/35	0/76	30	17	4	91
29/3	23/0	0/55	54/3	37/3	250	195	302	14	7	1	63	15	21/66	1/02	23	8	0	92
28/6	23/4	0/55	51/5	35/3	260	190	309	16	9	1	60	17	20/95	0/93	23	10	1	93
29/4	25/0	0/56	45/8	34/9	265	190	302	24	10	5	43	20	30/47	0/68	37	26	12	94
30/7	25/4	0/54	42/7	32/2	250	185	321	23	14	2	54	18	23/17	0/84	28	16	4	95
29/9	27/1	0/54	44/2	32/2	265	195	312	20	12	2	57	16	23/24	0/92	27	13	2	96
31/8	25/6	0/54	48/1	35/4	270	200	331	19	10	2	59	14	23/19	0/96	27	13	2	97
28/1	25/3	0/55	49/6	40/1	240	180	309	22	8	0	57	17	22/92	0/91	27	12	1	98
28/9	26/0	0/54	51/8	39/0	295	205	302	14	8	1	60	16	22/00	0/96	24	10	1	99

31/2	23/7	0/54	46/3	33/7	290	200	305	18	8	1	57	17	22/25	0/90	25	12	2	100
29/1	22/8	0/54	39/9	28/5	265	185	292	27	17	3	49	21	23/95	0/74	30	18	5	101
28/8	23/3	0/54	37/8	26/3	285	195	318	28	18	3	49	19	25/81	0/78	32	19	5	102
29/8	21/9	0/54	46/1	36/0	230	185	318	23	9	0	57	17	22/18	0/89	26	12	1	103
29/5	24/1	0/53	56/6	41/2	265	195	302	15	6	1	61	15	22/32	0/98	24	10	1	104
30/7	25/4	0/53	54/5	40/8	240	180	309	13	6	1	62	16	21/00	0/98	22	8	0	105
29/1	24/1	0/54	49/9	35/9	245	180	334	26	16	2	50	20	24/21	0/79	29	16	2	106
29/4	25/6	0/53	51/8	38/0	245	180	325	26	16	2	51	19	24/90	0/81	30	17	2	107
31/3	25/7	0/54	45/0	31/9	235	165	299	29	19	4	51	20	24/27	0/80	30	17	2	108
30/3	25/1	0/54	45/1	30/8	220	155	299	25	16	5	50	20	24/08	0/77	30	17	3	109
29/0	24/6	0/53	50/0	40/1	250	185	309	26	18	4	54	23	19/46	0/78	23	11	1	110
28/6	24/0	0/53	44/6	33/8	240	180	299	25	17	3	53	20	23/05	0/81	28	14	2	111
31/7	25/7	0/54	52/6	39/8	265	195	309	16	6	2	64	16	20/18	0/99	20	6	0	112
30/8	25/6	0/53	52/0	40/5	260	190	302	14	6	1	61	16	21/52	0/96	23	9	0	113
26/6	22/6	0/54	37/1	31/1	245	170	352	32	23	7	49	19	25/34	0/78	32	20	4	114
28/1	24/9	0/54	48/6	39/9	265	190	295	27	17	3	53	19	23/47	0/82	29	16	2	115
28/6	25/2	0/54	50/6	39/7	270	195	325	24	15	2	50	20	24/25	0/78	30	17	5	116
30/2	22/7	0/54	55/1	40/8	295	220	321	10	5	1	62	17	20/63	0/97	21	7	0	117
30/9	25/6	0/53	53/1	42/1	290	215	299	18	10	2	59	16	22/40	0/94	25	11	1	118
28/0	22/7	0/55	46/6	38/4	285	195	292	18	9	1	57	16	23/78	0/92	28	13	2	119
28/2	24/3	0/55	51/4	38/0	275	195	302	16	9	1	59	16	22/20	0/94	25	11	1	120
28/4	22/4	0/56	47/9	32/2	240	165	305	28	19	6	47	21	25/88	0/75	32	18	3	121
27/9	23/1	0/58	43/7	32/9	230	175	309	26	17	3	50	18	25/48	0/80	32	19	5	122
27/8	21/4	0/56	51/7	39/5	280	195	334	25	12	3	48	19	26/85	0/78	33	20	6	123
27/4	22/8	0/59	44/7	32/8	270	190	299	27	15	3	49	19	25/82	0/80	32	18	2	124
30/1	22/6	0/56	56/3	42/1	295	215	299	12	5	1	62	16	21/24	0/97	22	8	0	125
30/5	23/2	0/56	51/0	36/5	270	190	288	17	7	2	58	16	23/31	0/94	26	12	1	126
27/7	22/3	0/58	43/2	31/5	215	145	309	26	17	4	49	20	24/98	0/77	31	18	3	127
30/1	25/2	0/56	49/6	34/6	305	220	302	20	7	1	60	16	22/44	0/66	25	10	1	128
27/5	23/3	0/56	45/5	35/3	260	190	309	26	14	3	51	20	23/70	0/78	29	16	4	129
26/8	23/5	0/56	45/2	34/5	285	210	292	23	13	3	51	18	25/57	0/83	31	17	3	130
30/2	23/6	0/56	53/4	39/1	260	185	302	6	6	1	59	16	22/40	0/94	25	10	0	131
29/0	24/0	0/56	47/4	30/7	275	195	302	17	8	2	54	20	20/00	0/76	26	16	7	132
29/9	25/1	0/56	44/1	31/8	275	195	299	22	8	2	58	16	23/42	0/94	27	12	1	133
27/8	22/7	0/57	50/4	34/4	265	185	318	25	16	4	50	19	25/05	0/81	31	17	2	134
29/8	22/3	0/57	45/8	37/7	270	195	295	20	8	2	58	16	22/74	0/93	25	11	1	135
29/6	25/9	0/54	45/3	24/1	180	120	331	21	12	4	56	18	21/88	0/87	25	12	2	136
28/8	23/5	0/53	47/9	32/0	295	200	334	27	14	4	48	21	25/55	0/76	31	18	4	137
28/5	25/0	0/54	51/5	39/2	270	190	337	24	12	3	49	20	25/63	0/78	31	18	5	138
31/0	24/5	0/53	49/7	34/8	290	210	295	16	7	2	59	16	22/23	0/93	25	11	1	139
31/0	24/6	0/53	48/9	34/5	305	225	315	20	10	3	55	18	22/56	0/86	27	14	3	140
31/5	25/2	0/54	52/0	38/7	280	205	309	21	8	2	51	22	21/63	0/76	27	16	4	141
30/8	25/4	0/56	55/6	33/4	240	165	309	25	15	6	50	19	25/97	0/81	32	18	3	142
28/7	23/6	0/56	57/3	40/2	265	190	357	20	11	2	50	19	25/47	0/81	31	17	3	143
28/9	23/7	0/54	53/5	32/3	295	215	315	11	4	1	65	16	20/32	1/01	20	6	0	144
31/6	23/9	0/54	55/0	41/1	305	230	309	16	8	2	60	18	20/64	0/92	22	9	1	145
31/1	24/6	0/56	60/8	38/5	290	215	321	15	5	1	63	17	20/28	0/96	21	7	0	146
27/8	21/6	0/57	52/8	37/8	285	215	325	25	12	3	50	18	25/51	0/81	31	17	3	147
28/6	23/2	0/55	49/8	34/0	305	230	318	21	6	1	61	15	22/26	0/98	24	9	0	148
27/6	20/4	0/57	43/8	28/7	255	180	299	25	13	4	52	19	23/88	0/81	29	15	2	149
26/3	21/7	0/57	47/9	34/8	250	175	318	25	14	4	51	19	25/14	0/81	31	17	2	150
26/1	21/7	0/57	46/4	35/1	275	200	325	21	12	2	52	17	25/25	0/85	31	16	2	151
26/5	22/1	0/57	48/2	36/6	295	215	312	18	7	2	60	17	21/66	0/94	24	10	0	152
28/0	22/5	0/57	48/7	36/5	290	210	362	16	13	7	58	17	22/16	0/92	25	11	1	153
29/2	24/4	0/56	56/7	39/3	265	180	312	20	7	2	59	17	21/93	0/93	24	10	1	154
27/8	23/1	0/57	54/6	36/2	255	175	334	25	12	3	53	18	24/10	0/84	29	15	2	155
27/9	17/7	0/58	40/7	28/6	215	140	337	31	20	8	46	18	29/80	0/75	37	24	9	156
28/9	22/2	0/55	44/2	30/9	280	205	285	32	13	3	46	17	30/03	0/82	37	21	5	157
25/9	22/9	0/55	40/6	30/2	270	200	309	31	12	3	47	16	30/13	0/84	37	22	5	158
26/7	23/2	0/55	50/6	34/2	285	210	321	30	12	2	48	17	28/37	0/82	35	20	5	159
28/5	22/8	0/55	47/2	32/7	280	205	313	20	7	2	59	16	22/76	0/94	25	10	1	160
28/3	23/0	0/55	47/2	35/1	290	215	317	19	6	2	60	17	21/50	0/94	23	9	0	161
29/6	23/3	0/56	50/3	36/0	280	200	293	22	9	3	58	16	23/02	0/94	26	12	2	162
27/9	22/0	0/56	50/9	36/4	270	195	305	30	15	3	49	17	27/85	0/82	34	20	5	163
22/5	16/1	0/56	43/4	30/8	220	145	321	25	13	5	49	18	26/39	0/80	32	19	5	164
31/4	25/2	0/56	47/4	32/1	230	155	305	25	14	4	50	19	25/61	0/81	31	16	2	165
31/1	21/8	0/57	43/4	28/5	290	210	293	27	16	4	48	17	28/45	0/83	35	20	3	166
30/2	20/2	0/56	41/0	27/8	270	190	293	26	16	4	50	17	27/29	0/84	33	18	2	167
34/6	23/3	0/56	49/8	32/1	290	215	285	11	5	1	61	15	22/54	1/00	24	9	0	168
29/7	23/6	0/56	48/6	31/0	340	260	297	11	5	1	54	17	22/14	0/75	28	19	10	169
28/7	20/2	0/57	43/3	28/6	250	130	293	30	19	6	48	18	28/32	0/80	35	21	3	170
32/3	25/3	0/56	53/8	38/5	280	200	301	15	6	1	62	16	21/06	0/97	22	8	0	171
29/1	23/9	0/56	52/7	35/1	270	190	293	25	14	3	52	17	26/12	0/86	32	17	2	172
34/0	25/7	0/54	42/8	29/1	245	170	316	27	18	5	48	19	26/82	0/79	33	19	3	173
29/1	23/1	0/55	47/1	30/9	270	190	327	26	16	4	52	17	25/51	0/86	31	17	2	174
33/0	24/2	0/55	38/9	26/9	260	180	323	20	12	3	52	18	24/60	0/83	30	17	4	175
33/0	22/7	0/55	51/0	34/4	270	195	289	10	4	1	62	15	21/87	0/99	23	8	0	176
33/0	25/5	0/55	50/1	35/2	280	200	297	10	5	1	61	16	21/53	0/96	23	8	0	177
27/9	21/6	0/55	46/6	38/0	315	230	323	13	4	0	60	17	21/24	0/92	23	9	0	178
30/5	23/5	0/53	48/8	37/5	230	155	344	22	18	4	51	20	23/61	0/80	29	15	2	179
34/9	24/9	0/55	51/3	35/8	260	180	316	20	6	1	60	16	22/26	0/95	25	10	1	180
33/5	23/1	0/55	52/5	38/5	250	175	323	25	13	3	52	18	24/28	0/83	30	16	2	181
26/9	19/6	0/56	43/1	25/6	205	135	343	26	19	8	44	21	28/60	0/69	35	24	10	182
33/5	24/1	0/53	60/2	41/8	260	185	301	13	5	2	61	16	21/79	0/97	23	9	1	183
33/0	24/0	0/56	60/1	40/9	255	180	301	13	5	2	62	15	21/90	1/00	23	9	0	184
28/9	21/6	0/54	49/3	35/5	270	190	334	26	15	3	48	19	26/49	0/78	32	19	3	185
27/8	21/3	0/54	48/2	35/4	250	175	348	21	15	4	51	20	23/54	0/79	29	16	2	186
33/0	25/3	0/54	53/8	41/0	260	185	320	20	5	1	59	17	21/60	0/93	24	9	0	187
30/5	20/3	0/53	46/5	27/7	250	175	316	28	19	6	48	20	26/47	0/77	33	19	3	188
28/9	22/6	0/53	50/4	35/1	275	185	339	21	15	5	48	21	25/55	0/76	31	18	3	189
33/0	24/5	0/55	53/3	35/1	265	185	301	13	5	1	59	16	22/58	0/95	25	10	1	190
33/4	22/4	0/53	50/9	33/5	275	190	297	13	6	1	59	16	22/25	0/94	24	10	1	191
33/5	26/6	0/54	53/2	35/5	270	190	316	18	6	1	61	17	21/09	0/94	23	16	0	192
30/6	23/1	0/54	45/9	31/4	260	185	330	24	13	4	52	19	24/40	0/83	29	16	2	193
31/9	22/0	0/54	39/5	29/9	235	165	327	24	16	5	48	20	25/82	0/76	32	19	3	194
31/9	21/1	0/54	45/9	31/5	255	180	320	22	15	5	46	17	29/74	0/80	36	22	6	195
34/3	26/0	0/55	55/0	36/1	295	205	289	12	6	1	60	15	23/14	0/98	26	11	1	196
32/9	25/3	0/54	51/3	35/3	305	215	305	12	5	2	61	15	21/71	0/98	23	9	0	197
33/6	24/5	0/54	56/1	39/3	290	215	301	18	5	1	62	16	21/32	0/98	22	8	0	198
30/1	21/7	0/54	42/6	31/4	250	175	312	26	14	4	46	18	29/48	0/79	36	22	4	199
33/3	23/9	0/55	52/9	35/0	290	210	297	11	5	1	62	15	21/87	0/99	23	9	0	200
32/3	22/9	0/55	55/4	38/0	300	215	301	12	6	2	60	16	22/16	0/95	25	10	1	201
30/2	19/8	0/56	50/3	32/4	240	165	327	25	17	6	49	20	24/67	0/78	30	17	3	202
34/0	24/6	0/54	55/7	39/7	280	195	305	20	5	2	60	16	22/37	0/95	25	10	1	203
31/4	22/9	0/55	46/2	34/5	270	185	285	35	19	6	44	16	32/58	0/81	40	24	5	204

In the first stage, the effect of the amount of particles between 3 to 30 microns on the compressive strength of 7 and 28 days mortar and concrete was investigated (Figure 5).

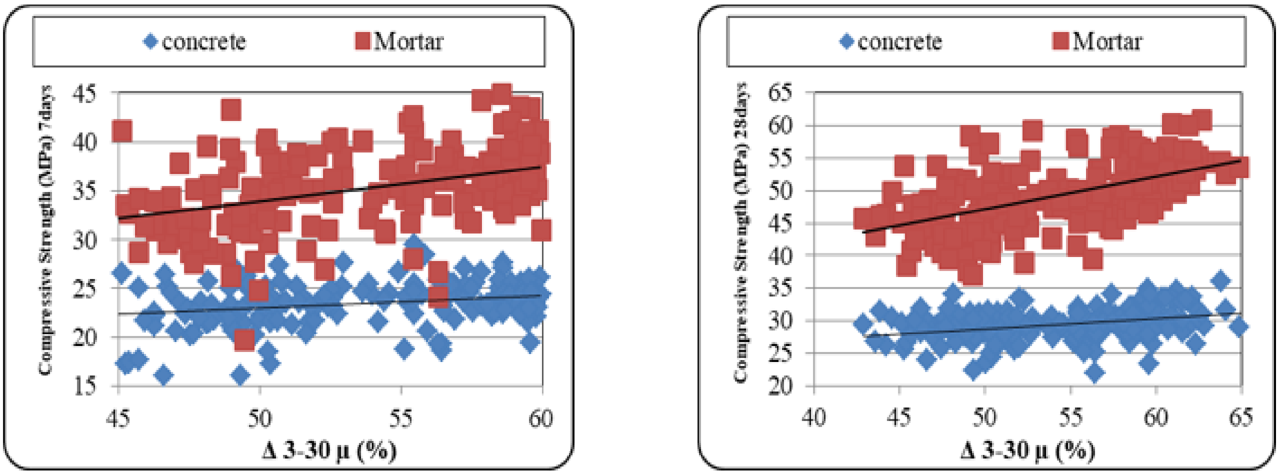


Figure 5. Diagrams of the effect of particle size between 3 to 30 microns on the compressive strength of 7 and 28 day mortar and concrete

Figure 5 Diagrams of the effect of particle size between 3 to 30 microns on the compressive strength of 7 and 28 day mortar and concrete As can be seen in the diagram, the compressive strength of standard mortar and concrete also increases with increasing the share of 3-30 micron particles, which is as follows:

(1) Compressive strength of mortar-28days (MPa) = 0/4978 (Δ3-30μ %) + 22/334

(2) Compressive strength of concrete-28days (MPa) = 0/1581 (Δ3-30μ %) + 20/847

Due to the fact that in concrete mixtures to achieve smoothness and slump, the amount of water and consequently the ratio of water to cement (w/c) varied, so the changes w/c of concrete mixtures relative to fine cement particles (3-0 microns) Checked out. Accordingly, with increasing the portion of fine cement particles, the demand for concrete increases, which leads to a decrease in the strength of concrete (Figure 6). On the other hand, with increasing the portion of fine cement particles, the amount of particles of 30-30 microns decreases, which leads to a decrease in strength.

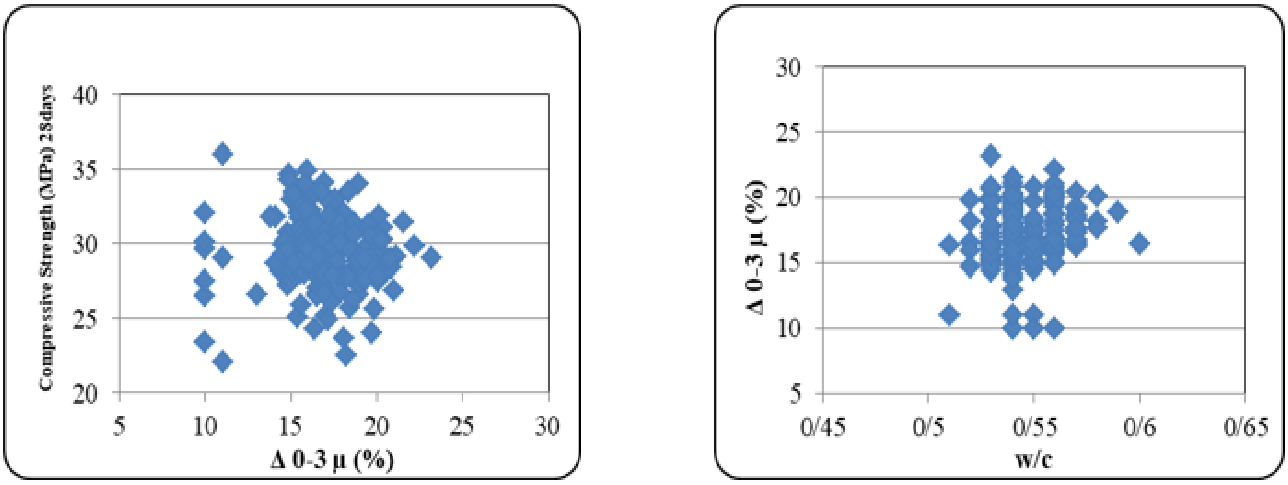
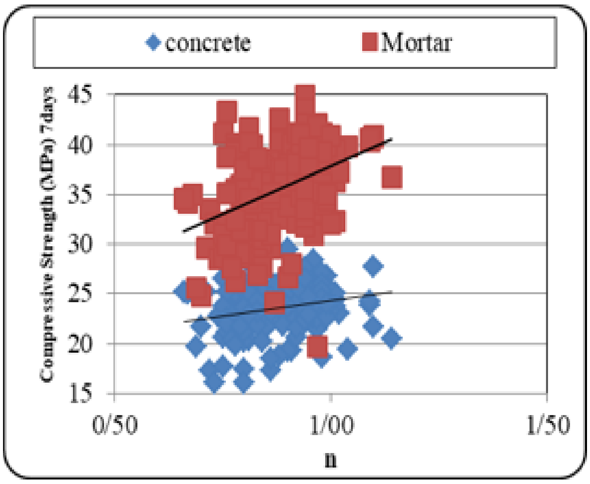


Figure 6. Graph of changes in the amount of 3-0 micron particles of cement in relation to w/c and 28-day compressive strength of concrete mixtures

Figure 7 shows the desired effect of increasing the uniformity coefficient (n) on the compressive strength of mortar and 7 and 28-day concrete. According to previous studies, with increasing the uniformity coefficient, the rate of hydration of cement increases, and as a result, the compressive strength also increases.



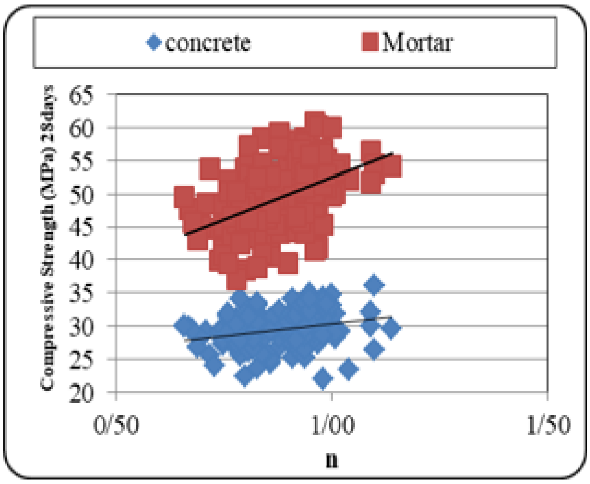
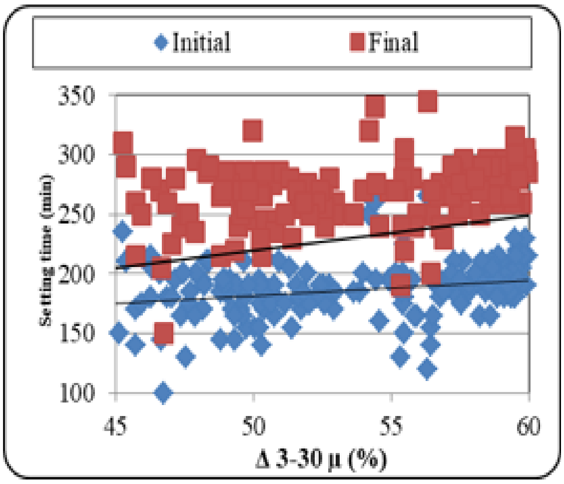


Figure 7. Diagrams of the effect of uniformity coefficient (n) on the compressive strength of mortar and concrete for 7 and 28 days

Also, with increasing the uniformity coefficient (n), the setting time of cement paste increases. The relationship between the amount of 3-30 micron particles and the setting time was also directly observed (Figure 8). It should be noted that in some cases, increasing the setting time of cement is undesirable.



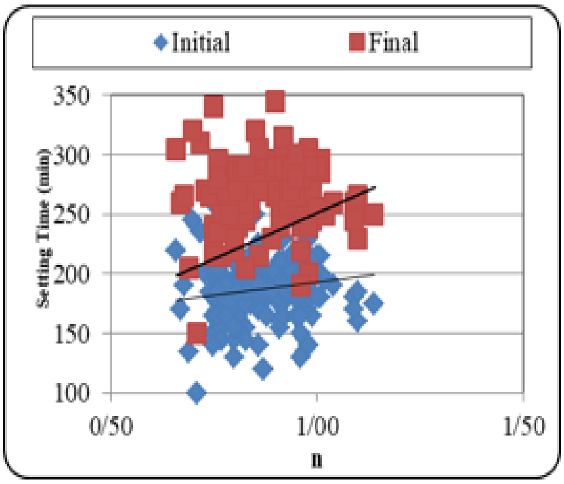


Figure 8. Diagrams of the effect of uniformity coefficient (n) on compressive strength of 7 and 28 day mortar and concrete

In the next step, the results on the 90-micron sieve by manual method and the residue on the 45 and 30-micron sieves by the alpine method were compared with the results of determining the percentage of material on the 90, 45, and 30 sieves by laser granulation method (figure 9). As expected, the correlation between the results in both alpine and laser methods was relatively high (R2=0.63), but between the results of manual and laser methods, this correlation was lower (R2=0.34).

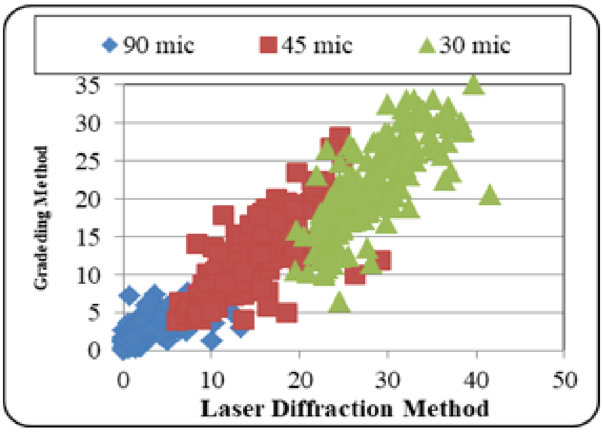


Figure 9. Diagram of the results of the parameters remaining on the sieve by alpine, manual and laser grading methods

4. CONCLUSION

According to the results of this study: 1. The compressive strength of standard mortar and concrete also increased with the increase of the share of 3-30 micron particles, which were presented; 2. The results of LD-PSD experiments were well correlated with the experiments remaining on the sieve by the alpine method; 3. The favorable effect of increasing the uniformity coefficient on the compressive strength of mortar and concrete for 7 and 28 days was observed; 4. With increasing uniformity or the number of particles of 3-30 microns, the setting time of cement paste increases (becomes longer);

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CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

5. REFRENCES

[1] Neville AM, Brooks JJ. Concrete technology. England: Longman Scientific & Technical; 1987 Mar. [View at Google Scholar]; [View at Publisher].

[2] Mehta PK, Monteiro PJ. Concrete: microstructure, properties, and materials. McGraw-Hill Education; 2014. [View at Google Scholar]; [View at Publisher].

[3] Duda, w."Cement data book". (1976), Volume 2. [View at Publisher].

[4] Neville AM, Brooks JJ (2002). "Concrete Properties". Prentice Hall, p22

[5] Bazari AA, Chini M. Laboratory Evaluation of Electrical Resistance of Concrete. Journal of Civil Engineering & Materials Application. 2022 Jun 1;6(2). [View at Google Scholar]; [View at Publisher].

[6] Chehrgani H. "Technology and Operation Handbook of Cement Factory" Publications of Cement Technology Scientific magezine. (2015).

[7] ASTM D422 "Standard Test Method for Particle-Size Analysis of Soils". (2002). [View at Publisher].

[8] ASTM C430 -96. "Standard Test Method for Fineness of Hydraulic Cement by the 45-µm (2003). (No. 325) Sieve" [View at Publisher].

[9] ASTM C115-96 "Standard Test Method for Fineness of Portland Cement by the Turbidimeter',(2003).. [View at Publisher].

[10] ASTM C204 ."Standard Test Method for Fineness of Hydraulic Cement by Air-Permeability Apparatus, (2000). [View at Publisher].

[11] Blott SJ, Croft DJ, Pye K, Saye SE, Wilson HE. Particle size analysis by laser diffraction. Geological Society, London, Special Publications. 2004;232(1):63-73. [View at Google Scholar]; [View at Publisher].

[12] Altun O, Benzer H, Dundar H, Aydogan NA. Comparison of open and closed circuit HPGR application on dry grinding circuit performance. Minerals Engineering. 2011 Feb 1;24(3-4):267-75.. [View at Google Scholar]; [View at Publisher].

[13] Neville AM. Properties of concrete. London: Longman; 1995 Jan. [View at Google Scholar]; [View at Publisher].

[14] Bentz DP, Garboczi EJ, Haecker CJ, Jensen OM. Effects of cement particle size distribution on performance properties of Portland cement-based materials. Cement and concrete research. 1999 Oct 1;29(10):1663-71. [View at Google Scholar]; [View at Publisher].

[15] Balamuralikrishnan R, Saravanan J. Effect of addition of alccofine on the compressive strength of cement mortar cubes. Emerging Science Journal. 2021 Apr 1;5(2):155-70. [View at Google Scholar]; [View at Publisher].

[16] Soeren Worre Joergensen. "Cement grinding Vertical roller mills versus ball mills". MSc, General Manager, Engineering, Grinding Technology, F.L.SMIDTH, (2015). [View at Google Scholar]; [View at Publisher].

[17] Kafash A & Saeedi, M. "A study of cement fineness changes in mortar and concrete" Annual International Conference on Research in Civil Engineering, Architecture and Urban Planning and Sustainable Environment, Tehran, 15 December 2015.

[18] Quercia G, Hüsken G, Brouwers HJ. Water demand of amorphous nano silica and its impact on the workability of cement paste. Cement and concrete research. 2012 Feb 1;42(2):344-57. [View at Google Scholar]; [View at Publisher].

[19] Lynch AJ, Rowland CA. The history of grinding. SME; 2005. [View at Google Scholar]; [View at Publisher].

[20] Buchanan Jr CE. Analysis of the ASTM Round-Robin Test on Particle Size Distribution of Portland Cement: Phase I1. [View at Google Scholar]; [View at Publisher].

[21] Basha SI, Aziz A, Maslehuddin M, Ahmad S, Hakeem AS, Rahman MM. Characterization, processing, and application of heavy fuel oil ash, an industrial waste material–A Review. The Chemical Record. 2020 Dec;20(12):1568-95. [View at Google Scholar]; [View at Publisher].

[22] Ferraris CF, Hackley VA, Avilés AI. Measurement of particle size distribution in Portland cement powder: analysis of ASTM round robin studies. ASTM International; 2004 Dec 1. [View at Google Scholar]; [View at Publisher].

[23] Allen T. Particle size measurement. Springer; 2013 Nov 21. [View at Google Scholar]; [View at Publisher].

[24] Frigione G, Marra S. Relationship between particle size distribution and compressive strength in Portland cement. Cement and concrete research. 1976 Jan 1;6(1):113-27. [View at Google Scholar]; [View at Publisher].

[25] Kuhlmann K, Ellerbrock HG, Sprung S. Particle size distribution and properties of cement. Part I: Strength of Portland cement. ZKG International Cement-Lime-Gypsum, Edition B. 1985 Apr;38(4). [View at Google Scholar]; [View at Publisher].

[26] Osbaeck B, Johansen V. Particle size distribution and rate of strength development of Portland cement. Journal of the American

Ceramic Society. 1989 Feb;72(2):197-201. [View at Google Scholar]; [View at Publisher].

[27] Wang A, Zhang C, Zhang N. Study of the influence of the particle size distribution on the properties of cement. Cement and Concrete Research. 1997 May 1;27(5):685-95. [View at Google Scholar]; [View at Publisher].

[28] Aiqin W, Chengzhi Z, Ningsheng Z. The theoretic analysis of the influence of the particle size distribution of cement system on the property of cement. Cement and Concrete research. 1999 Nov 1;29(11):1721-6. [View at Google Scholar]; [View at Publisher].

[29] Mendes TM, Hotza D, Repette WL. Nanoparticles in cement based materials: A review. Rev. Adv. Mater. Sci. 2015 Feb 1;40(1):89-96. [View at Google Scholar]; [View at Publisher].

[30] Bentz DP, Jensen OM, Hansen KK, Olesen JF, Stang H, Haecker CJ. Influence of cement particle-size distribution on early age autogenous strains and stresses in cement-based materials. Journal of the American Ceramic Society. 2001 Jan;84(1):129-35. [View at Google Scholar]; [View at Publisher].

[31] Stark U, Mueller A. Particle size distribution of cements and mineral admixtures—standard and sophisticated measurements. In11th International Congress on the Chemistry of Cement (ICCC), Durban 2003 May (Vol. 1116). [View at Google Scholar]; [View at Publisher].

[32] Celik IB. The effects of particle size distribution and surface area upon cement strength development. Powder Technology. 2009 Jan 10;188(3):272-6. [View at Google Scholar]; [View at Publisher].

[33] Binici H, Aksogan O, Cagatay IH, Tokyay M, Emsen E. The effect of particle size distribution on the properties of blended cements incorporating GGBFS and natural pozzolan (NP). Powder Technology. 2007 Aug 25;177(3):140-7. [View at Google Scholar]; [View at Publisher].

[34] H.J. Hwang & S.H. Lee & W. J. Lee & W.K. Kim & E. Sakai & M. Diamon "Effect of particle size distribution of binder on the reological properties of slag cement." (2005).

[35] Hassani A. & Manavarian M. "Design and optimization of non-uniform grading of drilling cement in order to achieve the desired properties of slurry and cement stone" Journal of Petroleum Research, Fall 2013, Volume 23, Number 75, pp. 48-40.

[36] Arvaniti EC, Juenger MC, Bernal SA, Duchesne J, Courard L, Leroy S, Provis JL, Klemm A, De Belie N. Determination of particle size, surface area, and shape of supplementary cementitious materials by different techniques. Materials and Structures. 2015 Nov;48:3687-701. [View at Google Scholar]; [View at Publisher].

[37] Ferraris C, Garboczi E. Identifying improved standardized tests for measuring cement particle size and surface area. Transportation research record. 2013;2342(1):10-6. [View at Google Scholar]; [View at Publisher].

[38] Ghiasvand E, Ramezanianpour AA, Ramezanianpour AM. Effect of grinding method and particle size distribution on the properties of Portland-pozzolan cement. Construction and Building Materials. 2014 Feb 28;53:547-54. [View at Google Scholar]; [View at Publisher].

[39] Chen C, An X. Model for simulating the effects of particle size distribution on the hydration process of cement. Computers and Concrete, An International Journal. 2012 Mar;9(3):179-93. [View at Google Scholar]; [View at Publisher].

[40] Zhang B, Tan H, Ma B, Chen F, Lv Z, Li X. Preparation and application of fine-grinded cement in cement-based material. Construction and Building Materials. 2017 Dec 30;157:34-41. [View at Google Scholar]; [View at Publisher].

[41] Wu J, Feng M, Chen Z, Mao X, Han G, Wang Y. Particle size distribution effects on the strength characteristic of cemented paste backfill. Minerals. 2018 Jul 27;8(8):322. [View at Google Scholar]; [View at Publisher].

[42] Kim D. Effect of adjusting for particle-size distribution of cement on strength development of concrete. Advances in Materials Science and Engineering. 2018 Apr 15;2018. [View at Google Scholar]; [View at Publisher].

[43] Zhang X, Guan X, Ma C. Characterization of hydration depths of cement particles with different sizes in hardened cement-based materials. Construction and Building Materials. 2021 Sep 20;300:123986. [View at Google Scholar]; [View at Publisher].

[44] Youness D, Yahia A, Tagnit-Hamou A. Development of viscosity models of concentrated suspensions: Contribution of particle-size and shape indices. Construction and Building Materials. 2022 Sep 5;346:128335. [View at Google Scholar]; [View at Publisher].

[45] Farhadi S (2007) "Determining the best grading range for cement and increasing production and optimizing electricity consumption in cement mills". Sixth National Energy Conference.

[46] Aiqin W, Chengzhi Z, Ningsheng Z. The theoretic analysis of the influence of the particle size distribution of cement system on the property of cement. Cement and Concrete research. 1999 Nov 1;29(11):1721-6. [View at Google Scholar]; [View at Publisher].

[47] Behfar R and Davarnejad R. (2019). "The Impact of Improving Grading Distribution on Cement and Concrete Strength". Fifth National Conference on Cement Industry and the Future Horizon, Tehran.

[48] "Guide to the National Method of Concrete Mixing Design", Building and Housing Research Center, p33.