Journal of Sustainable Construction Materials and Technologies, Vol. 6, No. 1, pp. 12-23, March 2021
Yildiz Technical University Press, Istanbul, Turkey
https://doi.org/10.29187/jscmt.2021.55

Contents lists available at YTUEJS

Journal of Sustainable Construction Materials and Technologies

https://jscmt.org/

e-ISSN: 2458-973X

Research Article

Influence of Marble Powder and Fly Ash on Rheological Properties and Strength of Cementitious Grouts

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Abstract

The usability of two environmentally important waste materials in cementitious fine grout production was investigated as partial replacement materials. The study is very important in reducing carbon footprint and cost in construction industry, and improving cement properties. The influence of replacement materials on flowability and strength was investigated by rheological and compressive strength tests. With marble powder replacement, a compressive strength of 26 MPa was achieved, which was fairly above the minimum compressive strength of 14 MPa. The flowability and strength of the mixes were heavily dependent on W/C ratio and affected by type and amount of replacement materials. Increasing W/C ratio and fly ash amount increased flowability, but inversely affected strength of the grouts. On the other hand, marble powder was found to increase the strength to a large extent, but decreased the flowability. The highest increase of 24 % and the lowest increase of 5.3 % on average were achieved with 10 % fly ash and 20 % marble powder replaced mixes, respectively. The rheology data, obtained in a wide shear stress-shear rate range, were found very useful in explaining flowability as well as setting behavior (rate) of grout mixes.

Keywords: Grout; fly Ash; Marble Powder; Rheology; Compressive Strength

1. Introduction

Grout is a cementitious material, primarily composed of Portland cement and fine size aggregate combined with sufficient amount of water to produce a flowable mix [1]. Cementitious grout differs from concrete in that it contains finer aggregate and has a higher water/cement ratio. Grout is used to fill space or cavities and provide continuity between building elements and to structurally bond wall elements into a wall system [1]. ASTM C476 [2] specifies conventional cementitious grout either by proportions of the mix materials by volume or by compressive strength of hardened grout. The standard also classifies grout as either fine or coarse grout depending on the size of aggregate used. Fine grout uses only fine aggregate with a maximum size of 3/8 inches, whereas coarse grout uses both, fine and coarse aggregate with a maximum size of 1/2 inches. Among the grout ingredients, cement is the most expensive and has the largest carbon footprint due to carbon dioxide release and energy consumption during manufacturing. Reducing the amount of cement consumption in concrete (or mortar or grout) by partial replacement can reduce the carbon footprint and cost. Construction industry is searching for supplementary or partial replacement materials with the objective of reducing cost and pollution and improving the properties of cement products.

This paper was recommended for publication in revised form by Editor Orhan Canpolat
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https://doi.org/10.29187/jscmt.2021.55
Received 15 January 2021; Received in revised form 12 February 2021; Accepted 25 February 2021, Available online 31 Mart 2021

Cement-based grouts with various mineral additives (such as bentonite, silica fume, fly ash, limestone powder) have been used in modern practice for various grouting applications [3]. Pozzolanic materials (e.g., fly ash and silica fume, blast furnace slag) or fine minerals (e.g., limestone powder or marble powder) contribute to certain properties of fresh and hardened concrete through hydraulic or pozzolanic activity or both. Fly ash is a cost effective cementitious material, which is utilized very commonly in manufacturing of cement or cement products (e.g., concrete, mortar or grout). When used, it reduces the amount of cement and improves flowability and spreading ability of grout [4,5]. It was also found that fly ash delays setting of grout, but could improve its compressive strength at long (e.g., 90-day or longer) aging periods [5-8].

Marble powder is a waste by-product generated as sludge in marble processing factories during sawing, honing and polishing. Marble powders constitute one of the important environmental problems all over the world as they can occupy large land areas, reduce the fertility of soil due to high alkalinity and contaminate underground water. On the other hand, they are valuable product, which can be mixed with concrete or cement to make blocks, building stones, floors and many other objects [9].

Flowability (or consistency) and strength are among the most important parameters of fresh and hardened cementitious grouts, respectively [10]. During application, flowability should be maintained so that grout can easily flow into the smallest grout spaces and around any obstructions, such as reinforcing bars, joint reinforcement, anchors, ties and small mortar protrusions. High initial flowability is needed when grout is used in congested or small spaces due to water adsorption by the masonry before and after grout placement [11]. Flowability is mainly a function of viscosity and can be increased solely by adding water, but free (unreacted) water can cause segregation, bleeding, higher shrinkage and porosity and hence causes a decrease in grout strength. Therefore, fluidity of the grout during application should be maintained, but no segregation or bleeding should be allowed.

In literature, flowability of cement grout is mainly determined by pipe flow, Marsh funnel, mini-slump and rheological tests [12,13]. There is no any specific ASTM standard on determination of flow behavior of grout, but various standards are utilized for this purpose. For example, ASTM C143 [14], which describes "standard test method for slump of hydraulic-cement concrete" is generally utilized to determine grout flowability as explained in ASTM C476 [2]. Alternatively, ASTM C939 [15] which specifies "the flow of grout for preplaced-aggregate concrete" can be also utilized to study the flowability of grouts. Rheology is a study of flow and deformation behavior of slurries and ASTM C1749 [16] specifies the measurement of rheological properties of hydraulic cementitious paste by using a rheometer. Since rheometers can test very dilute or very thick slurries, they can be used in testing fresh cementitious grout mixes, the obtained rheological parameters (e.g., apparent viscosity, yield stress, thixotropy as well as structural breakdown or build-up properties during shearing) can be related to flowability of grout. Flowability of grout mix is time dependent due to development of the bonds between the ingredients. Most of the common techniques may suffer from time-dependent physical or chemical changes, which can occur until testing the flowability [12]. Roussel and Le Roy [17] stated that for certain funnel geometries and test conditions, the flow time is a measure of flowability that can be related to the plastic viscosity and yield stress of grouts behaving as Bingham fluids. Investigations on natural hydraulic lime (NHL) grouts [18] and cement based grouts [19] exhibited a good correlation between classical flow tests and the rheological properties.

Even though the influence of incorporation of fly ash and marble powder as supplementary materials in concrete production was widely investigated, influence of these materials in fine grout production was not investigated to any great extent. In this study, the possibility of incorporating fly ash and marble powder in preparation of fine cementitious grout was investigated by partially replacing them for cement and aggregate. Interactions between the components (i.e., cement, water, aggregate, fly ash and marble powder) were inferred from rheological and strength data. The relation between flowability of freshly prepared grout and compressive strength of hardened grout was exhibited and the potential usage of fly ash and marble powder in grout mixes was assessed.

2. Materials and methods

2.1. Materials

Materials used in this study include Ordinary Portland Cement, fine aggregate, coal fly ash, marble powder and tap water. CEM I42.5R grade ordinary Portland cement manufactured by Seza Cement Factory in Baskil (Elazig, Turkey) was used in this study. Fine size aggregate (under 5 mm), produced from crushed carbonate rock, was received from local commercial aggregate production plant (Harput Concrete AŞ). The finer size fraction (under 850 μm) was separated by a standard test sieve and used in the tests. Fly ash, used as partial cement replacement material, was obtained from Soma (Turkey) coal power plant. Waste marble powder, used as partial aggregate replacement, was collected from a marble plant in Akçadağ (Malatya) region as slurry and then dried in oven at 60℃ in the laboratory.

The fly ash and dried marble powder were screened by a 300 μm standard sieve to remove any large foreign materials. Particle size distributions of aggregate, fly ash, and marble powder were measured by laser diffraction technique using Malvern Mastersizer 2000 Particle Size Analyzer (Malvern Instruments Ltd., United Kingdom) and the results are presented in Figure 1. We can see that the fine size aggregate, fly ash and marble powder have mean particle sizes of about 191, 45 and 10 μm, respectively. Blaine specific surface area and specific gravity of the components were also determined and presented in

Table 1 which shows that the fine marble powder has a much higher specific surface area of 7000 cm^2/g than fine aggregate (1171 cm^2/g).

Table 1. Blaine surface area and specific gravity of the grout components

Component	Blaine surface area, cm^2/g	Specific gravity, g/cm^3
Portland cement	3658	3.12
Aggregate	1171	2.80
Fly ash	4013	2.30
Marble powder	7006	2.61

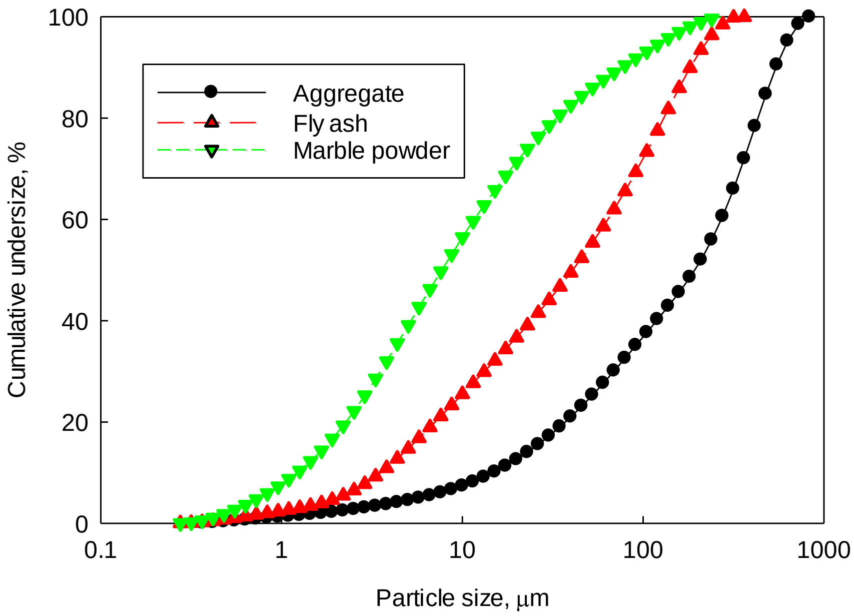

Figure 1. Particle size distribution of aggregate, fly ash and marble powder.

Table 2. XRF analysis of the grout components

Component, %	SiO_2	Al_2O_3	Fe_2O_3	P_2O_5	MgO	K_2O	CaO	SO_3	TiO_2
Fly ash	33.92	2.56	3.31	0.44	6.66	3.40	44.96	3.66	0.78
Marble Powder	0.42	-	0.68	-	0.34	-	98.39	-	-
Aggregate	0.83	-	1.25	-	0.23	-	97.36	-	-

The chemical and mineralogical compositions of aggregate, fly ash and marble powder were determined by XRD (Rigaku Geiger D-Max/B, Japan) and XRF (Spectro Xepos, Spectro Analytical Instruments GmbH, Germany) instruments. The XRD and XRF data are presented in Figure 2 and Table 2, respectively. As seen from Figure 2, the XRD patterns of aggregate and marble powder perfectly overlap which depict that both materials are basically calcium carbonate. XRD and XRF results also showed that the fly ash is rich for carbonates and cannot be considered as class F or class C according to ASTM C618 standard [20].

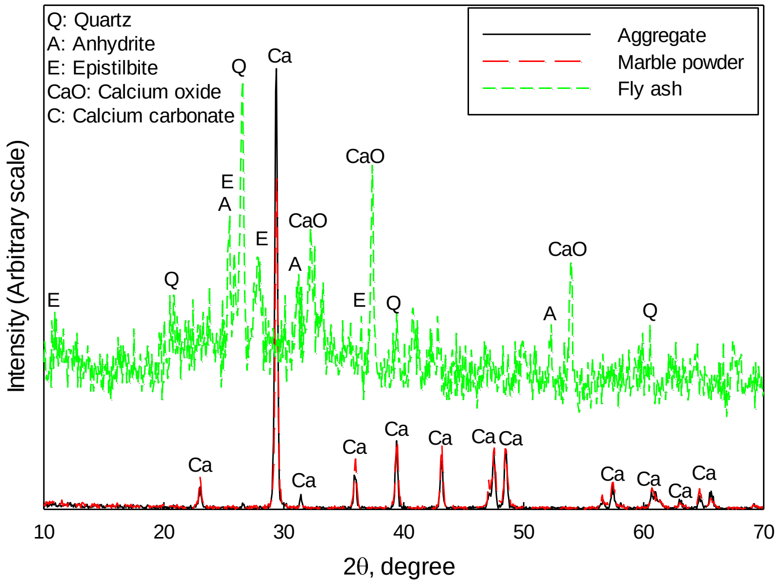

Figure 2. X-ray diffraction analysis of aggregate, fly ash and marble powder.

2.2. Methods

ASTM C476 standard [2] specifies the cement grout by proportion of ingredients or on the basis of compressive strength. The grout mixes were prepared to meet the fine cement grout specifications by proportion of ingredients. The samples were prepared at different W/C ratios in the absence and presence of fly ash and marble powder as replacing materials for cement and aggregate, respectively. Flowability of fresh mixes and strength of the hardened grout were evaluated. The influence of replacing materials was investigated at the ratios of 10 and 20 % on weight basis and the W/C ratio was varied between 1.0 and 1.4 while keeping the cement aggregate (C/AG) ratio constant at 3.0. Due to high specific surface area of the ingredients and absence of water reducing agent, high W/C ratio is required to obtain workable mixes. The mixes prepared at W/C ratio below 1.0 (at constant C/AG ratio of 3.0) were too thick (or viscous) and were not workable to carry out rheology test by the utilized set-up.

2.2.1. Rheology tests

The rheology measurement of the mixes was performed by Brookfield R/S+ rheometer from Brookfield Engineering Laboratories Inc. (MA, USA). The instrument is equipped with coaxial vane type spindle, cylindrical sample cell (cup) and a water jacket. The computer-operated rheometer utilizes the Rheo3000 software, which is capable of describing the rheological behavior of the mixes by fitting well-known rheological models to the shear stress – shear rate data. The model with the least standard error and highest correlation coefficient is recognized as the best-fit by the software. The temperature of the medium, controlled by Brookfield Circulating Bath with Digital Controller, was maintained at 20 °C for all measurements. All of the measurement variables (shear rate, temperature, measurement time etc.) were set and the spindle was placed before preparing the mix. Since the time between transferring the prepared mix into the sample cup and executing rheology test was very short (about 10 s), the mixes did not require pre-shearing. Shear rates from 0 to 600 1/s and then from 600 to 0 1/s were set as ascending and descending shear steps, respectively. The elapsed (measurement) time was kept constant as 300 s for each step.

In order to obtain reproducible results, a proper homogenization of fine ingredients is crucial. For each test, a total of 125 ml of suspension was used and the suspensions were prepared as described below;

1. All materials were precisely dry-weighted and hand mixed in a 250 ml beaker for 15 seconds by a stainless steel spatula.
2. The water is added slowly into the beaker while mixing and was mixed further for 30 seconds.
3. The mix was mixed for 60 seconds at about 600 rpm by Heidolph Hei-Torque 100 mixer equipped with a blade and immediately transferred into sample cup of the rheometer.
4. After placing the sample cup, the measurement was executed immediately at controlled shear rates (CSR).

2.2.2. Sample preparation and uniaxial compressive strength tests

Three specimens for each mix design, prepared as described above, were poured into 50 mm cubic steel molds as two layers and consolidated by hand tamping. After 24 h, the mold was removed and immediately immersed into lime containing water at 20 °C for curing. The compressive strength test was carried out on 28 and 90-day cured cubes. The tests were carried out in accordance with ASTM C109 standard [21] by using a 2000 kN capacity uniaxial compression test equipment from U-Test (Ankara, Turkey). The load was applied at 1400 N/s rate until the specimen failed. Load at the failure divided by the area of specimen gave the compressive strength of grout. Only average compressive strength value, obtained from three identical specimen for each mix design, was reported as the result for brevity.

3. Experimental results

3.1. Rheology results

Firstly, the flow properties of mixes, prepared between 1.0 and 1.4 W/C ratios in the absence of replacing materials, were determined. Mixes were subjected to ascending and then descending shearing rates between 0–600 and 600–0 1/s and the data are presented in Figure 3(a). The mixes prepared at the same W/C ratios in the presence of replacing materials were subjected to similar rheological tests and the results are presented in Figures 3(b-g). Scales of the figures were kept constant for easy comparison. Visual inspection shows no evidence for structural breakdown of the mixes over the studied shear rate range. But, the rheograms show important differences (thixotropy) in shear stress-shear rate plots between the ascending and descending shear steps in this wide range. For given shear rates, generally higher shear stresses were obtained during descending step. It is considered that viscosity of grout is time dependent due to development of bonds and setting of mixes takes place steadily despite continuous mixing. For a given shear rate, an increase in shear stress is observed with decreasing W/C ratio and increasing marble powder content, while an opposite trend is observed with fly ash (Figures 3(a-g)). The differences were explained in term of setting rate and formation of hydration products (e.g., calcium carbosilicate hydrate) as well as in terms of shape and filling ability of the particles. It is safe to state that low W/C ratio mixes are less flowable [10] and set faster than high W/C ratio mixes. Jiang et al. [13] investigated rheology, strength and hydration characteristics of mortars and found addition of limestone unfavorable for fluidity.

The mixes do not exhibit Newtonian (Eq. 1) behavior and deviation from Newtonian behavior increases with decreasing W/C ratio. The Rheo3000 software recognized Ostwald or power law model (Eq. 2) as the best-fit for the samples and the calculated correlation coefficient values were above 0.97. Grouts, prepared without or with replacing materials, exhibited shear thinning behavior, but the replacing materials influenced the flow differently. Bingham plastic (Eq. 3) and Herschel-Bulkley (Eq. 4) model flows, having a yield stress (τ_0) parameter in their equation, were also suggested for cement products (such as concrete, mortar, grout or paste) by some reseachers [13,19,22-24].

$$\tau=\eta\dot{\gamma} \quad (1)$$
$$\tau=K\gamma^n \quad (2)$$
$$\tau=\tau_0+\eta_p\dot{\gamma} \quad (3)$$
$$\tau=\tau_0+K\gamma^n \quad (4)$$

As rheology parameters, the constants K (in unit of Pa sn) and n (no unit) in Eq. 2 represent consistency coefficient and flow index, respectively. K is a measure of the consistency of the fluid such that, the higher the K, the more viscous the fluid. Whereas, n is a measure of the degree of non-Newtonian behavior such that, the greater the departure from unity (one), the more pronounced the non-Newtonian property [18,25,26]. The equation constants were calculated by the Rheo3000 software and presented in Table 3. As seen from the table, the consistency coefficient increases with the presence of marble powder, but decreases with fly ash. In the presence of marble powder, flow indices generally depart more from unity, which indicates more deviation from Newtonian behavior. It can be anticipated that the mixes become more viscous and less Newtonian in the presence of marble powder, whereas less viscous and more Newtonian in the presence of fly ash. Similar conclusions were achieved by several authors who investigated effect of fly ash on rheological properties of hydraulic lime grouts [10] and cement mortars [13].

The results are in-line with apparent viscosities ($\Delta\tau/\Delta\dot{\gamma}$) of the mixes calculated by the Rheo3000 software. Apparent viscosity data were evaluated as a function of shear rate, but only ascending shear step data were presented in Figure 4. It is obvious that the mixes exhibit shear thinning behavior as apparent viscosities decrease with increasing shear rate. For example, the apparent viscosities of mixes with 1.0 and 1.4 W/C ratios decreased from 1.1 Pa.s to 0.3 Pa.s and from 0.3 Pa.s to 0.08 Pa.s, respectively. Increasing W/C ratio causes the apparent viscosity of grout to decrease and flowability to increase. The mixes with lower W/C ratio kept their apparent viscosities higher in the time range of the measurement, indicating relatively faster setting of these mixes.

The incorporation of fly ash improved the flowability of the mixes, irrespective of the W/C ratio. The replacement of 10 % fly ash had negligible effect but, the improvement was more pronounced when replacement was increased to 20 %. It can be said that fly ash reduced the water requirement to achieve a certain flowability, and increased the transportability and pumpability of cement grout. Quiroga-Flores et al. [5] investigated the effect of partial replacements of fly ash and sodium-activated betonite for Portland cement and found that fly ash improved the rheology whilst bentonite increased the thixotropy and shear thinning behavior of fresh grouts.

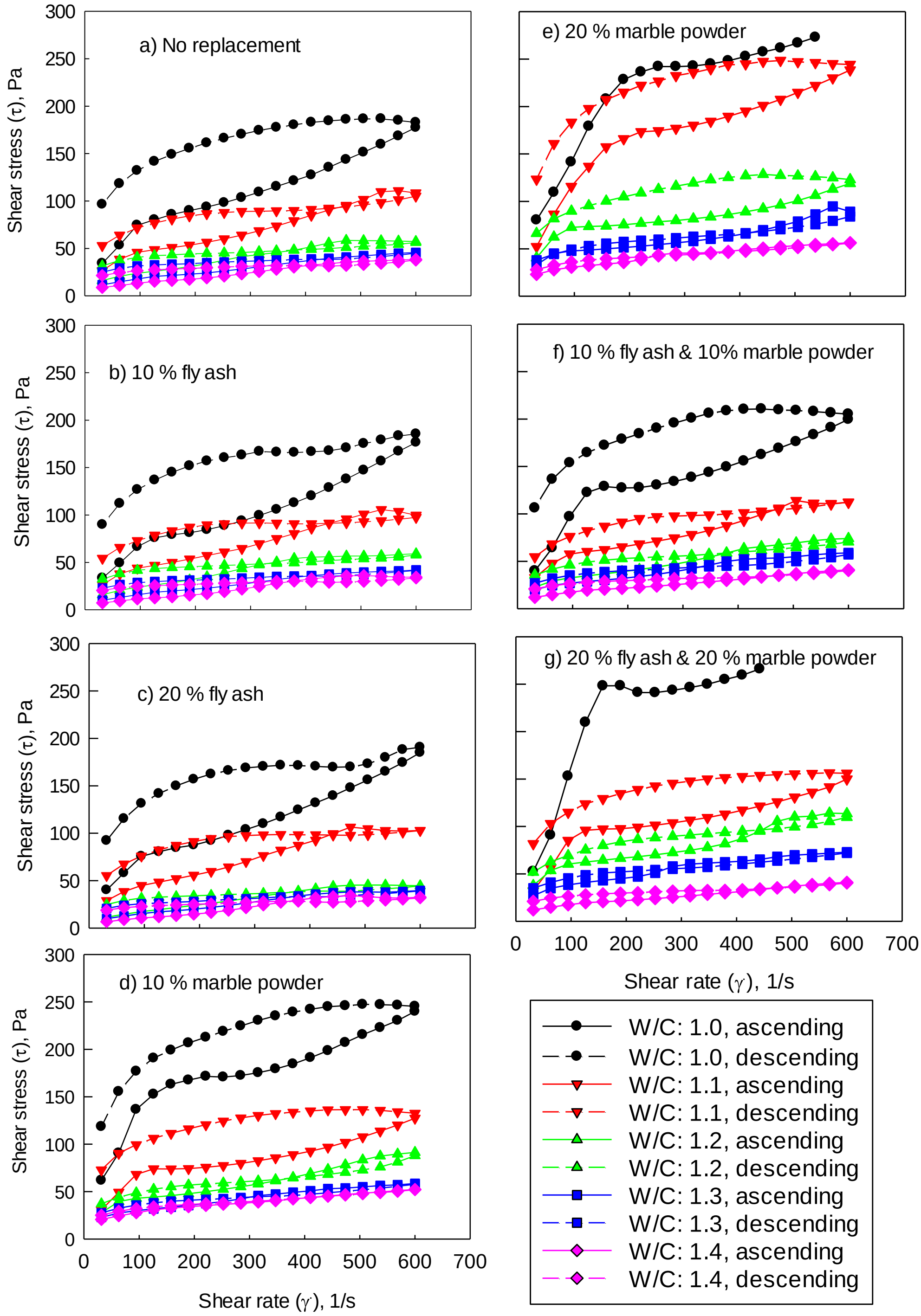

Figure 3. Shear stress-shear rate data of grout mixes prepared at different W/C ratios in the absence and presence of replacing materials.

Table 3. Mix design and replacement of fly ash and marble powder for cement and aggregate, respectively

W/C/AG ratio by weight	Replacement of fly ash or marble powder (by weight %)				Rheological parameters	
	Cement, %	Fly ash, %	Aggregate, %	Marble powder, %	Consistency coefficient, K	Flow index, n
No replacing material						
1.0/1/3	100	-	100	-	6.734	0.497
1.1/1/3	100	-	100	-	4.857	0.476
1.2/1/3	100	-	100	-	2.659	0.487
1.3/1/3	100	-	100	-	1.923	0.489
1.4/1/3	100	-	100	-	1.109	0.551
10 % Fly ash replacement						

1.0/1/3	90	10	100	-	5.699	0.515
1.1/1/3	90	10	100	-	4.827	0.475
1.2/1/3	90	10	100	-	2.563	0.498
1.3/1/3	90	10	100	-	1.527	0.518
1.4/1/3	90	10	100	-	1.000	0.557
20 % Fly ash replacement						
1.0/1/	80	20	100	-	7.719	0.476
1.1/1/3	80	20	100	-	5.136	0.473
1.2/1/3	80	20	100	-	1.636	0.526
1.3/1/3-	80	20	100	-	1.442	0.521
1.4/1/3	80	20	100	-	1.000	0.548
10 % Marble powder replacement						
1.0/1/3	100	-	90	10	23.430	0.361
1.1/1/3	100	-	90	10	9.546	0.389
1.2/1/3	100	-	90	10	7.00	0.384
1.3/1/3	100	-	90	10	6.424	0.340
1.4/1/3	100	-	90	10	2.397	0.429
20 % Marble powder replacement						
1.0/1/3	100	-	80	20	30.678	0.364
1.1/1/3	100	-	80	20	18.866	0.400
1.2/1/3	100	-	80	20	17.720	0.278
1.3/1/3	100	-	80	20	11.045	0.307
1.4/1/3	100	-	80	20	7.248	0.318
10 % Fly ash and 10 % marble powder replacement						
1.0/1/3	90	10	90	10	10.263	0.462
1.1/1/3	90	10	90	10	8.308	0.403
1.2/1/3	90	10	90	10	4.689	0.424
1.3/1/3	90	10	90	10	4.481	0.397
1.4/1/3	90	10	90	10	2.540	0.401
20 % Fly ash and 20 % marble powder replacement						
1.0/1/3	80	20	80	20	10.184	0.565
1.1/1/3	80	20	80	20	10.381	0.413
1.2/1/3	80	20	80	20	11.323	0.348
1.3/1/3	80	20	80	20	7.796	0.349
1.4/1/3	80	20	80	20	6.630	0.315

The improvement in flowability could be explained by the spherical shape of fly ash which made a lubricating effect between particles and reduced inter-particle friction that facilitated their flow. On the other hand, addition of marble powder influenced rheological properties of the mixes more than fly ash. The incorporation of very fine size marble powder significantly increased the apparent viscosity and reduced the flowability of the mixes. Rheology studies showed that the proportion of fines and hence increasing surface area of aggregates increased water demand in mortars [27] and cement pastes [23]. In other words, for a given (fixed) flowability, marble powder requires more water than aggregate due to increased surface area, and hence increased reaction with water [13]. It is also considered that, finer marble powders fill the voids between the larger aggregates, thereby make it more difficult for the solid particles to slide over each other during shearing. In binary replacements, given in Figures 4(f) and 4(g), addition of fly ash largely compensated the negative effect of marble powder on flowability.

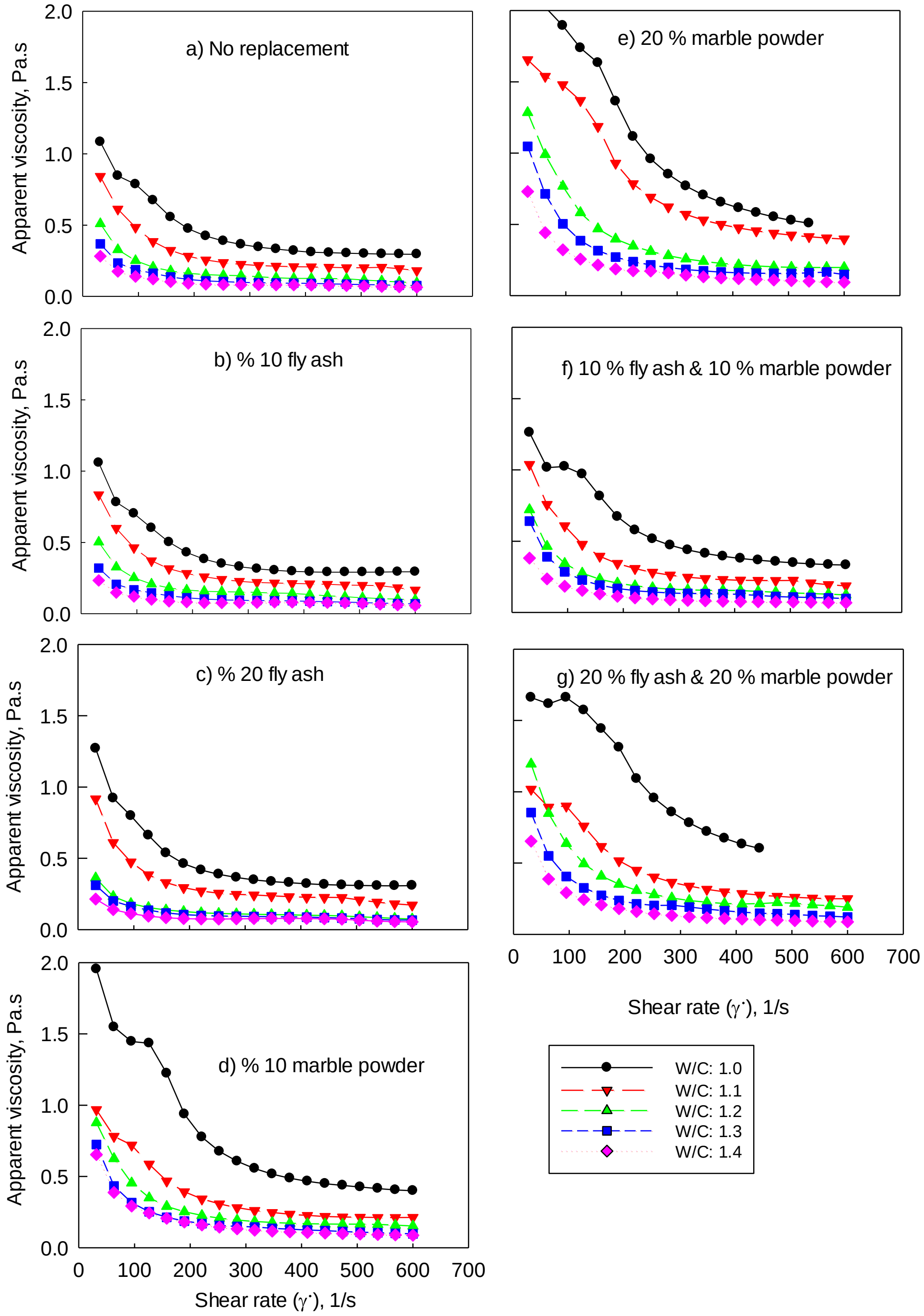

Figure 4. Apparent viscosity-shear rate of grout mixes prepared at different W/C ratio in the absence and presence of replacing materials.

3.1. Compressive strength test results

The compressive strength of grouts after 28 days and 90 days of aging was determined and the results were presented in Figure 5 and Figure 6, respectively. It can be seen from Figure 5 that the compressive strength is inversely proportional to the increase in W/C ratio, that is, the higher the W/C ratio, the lower the compressive strength. In the absence of replacement materials, the compressive strength decreased from 21.44 MPa to 7.36 MPa with increasing W/C ratio from 1.0 to 1.4. The reason for decrease in compressive strength with increasing W/C ratio is explained well in the literature. Free (unreacted) water causes pore (void) and crack generation in grout due to evaporation and can also cause bleeding and segregation during processing. ASTM C476 requires a minimum compressive strength of 2000 psi (~14 MPa) for 28 days cementitious grouts. As seen from Figure 5, grout mixes produced higher strength than specified compressive strength requirement at only 1.0 and 1.1 W/C ratios. Incorporation of 10 % and 20 % fly ash as cement replacement decreased compressive strength, respectively, by 10 % and 21 % on average at the studied W/C ratios. As known fly ash is pozzolanic material, which reacts chemically with calcium hydroxide in the presence of water to form additional calcium silicate hydrate (CSH), possessing cementitious properties. It is also known that fly ash particles increase the compactness in concrete by filling the spaces. But, the results showed that it could not perform as well as the replaced cement, because the fly ash could not develop CSH and, due to its relatively larger size, could not fill the voids between particles as much as the cement. The lubricating effect of fly ash particle, that increased the flowability of fresh mix, can be another reason for the reduced strength. Different results found in the literature can be explained by using different types of fly ashes (i.e., class C, class F or carbonate rich) which possess different type and amount of materials. It is also considered that the hardening rate can be low for carbonate rich fly ash. The beneficial effect of fly ash could be observed when used as aggregate replacement instead of cement replacement or at curing times longer than 28 days. We can see that, fly ash replaced samples with only 1.0 W/C ratio resulted in the minimum compressive strength value of 14 MPa.

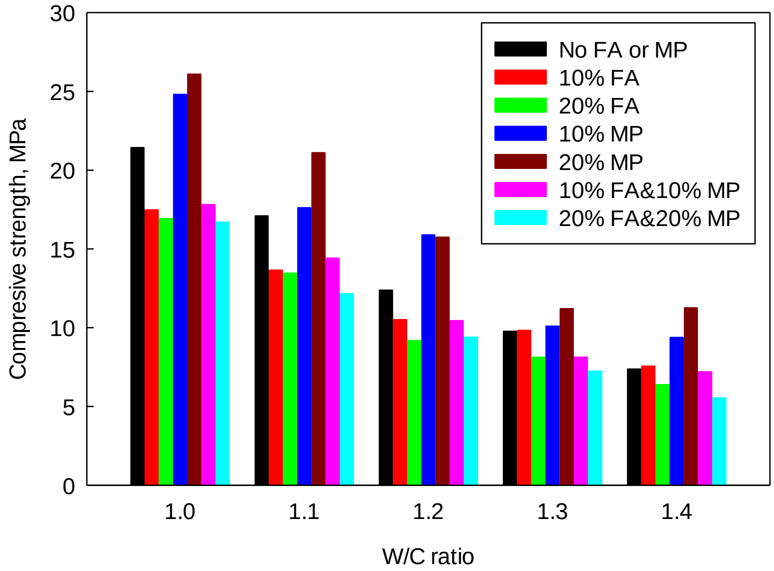

Figure 5: 28-day strength of hardened grouts prepared at different W/C ratios in the absence and presence of replacing materials

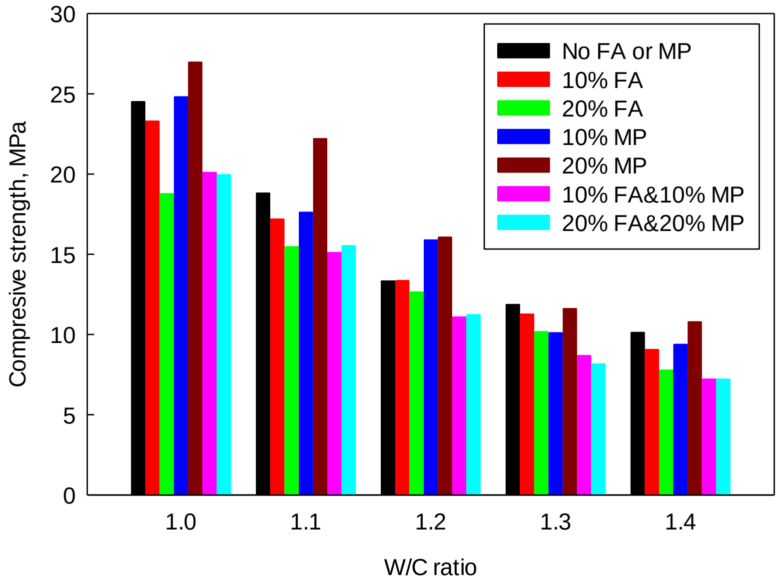

Figure 6. 90-day strength of hardened grouts prepared at different W/C ratios in the absence and presence of replacing materials

The replacement of 10 and 20 % marble powder for aggregate, respectively, increased the compressive strength about 15 and 23 % on average at the same W/C ratios. The mix prepared at 1.0 W/C ratio with 20 % marble powder replacement gained the maximum compressive strength of 26.09 MPa which is fairly above the minimum compressive strength of 14 MPa. It was possible to obtain hardened grouts with the required compressive strength from the mixes having W/C ratio not exceeding 1.2. The greater specific surface area of marble powder had a strong contribution to the mechanical strength by by different ways as delineated by several investigators. Dhanalaxmi and Nirmalkumar [28] stated that additional surface area can produce more nucleation sites for cement hydration products which are responsible for grout strength. Bentz et al. [29] studied limestone and silica powder as cement replacements and showed that limestone and silica surfaces were active sites for nucleation and growth of cement hydration products, while the limestone also led to the formation of carboaluminate hydration products. It is also considered that very fine size marble powder filled voids between particles, increased the compactness and hence reduced the porosity of hardened grout. Owing to its higher specific surface area, marble powder also reacted and consumed free water, which otherwise could cause weakness (e.g., pores, voids, cracks) upon evaporation, and at the same time prevented bleeding and segregation during processing.

The effect of W/C ratio and partial replacement materials on grout strength can be inferred from the comparable compressive strength values. Grouts without replacement material (prepared at 1.1 W/C ratio) gave a compressive strength of about 16 MPa which is comparable to 20 % marble powder replaced grout (prepared at 1.2 W/C ratio) and to 20 % fly ash replaced grout (prepared at 1.0 W/C ratio). The compressive strength of grouts at 90 days of aging was also measured and the results were exhibited in Figure 6. The strength of all mixes increased at different levels with the aging time. The highest and lowest increases in strength were achieved with 10 % fly ash (by 24 % on average) and 20 % marble powder (5.3 % on average) replaced mixes, respectively. On the other hand, the mixes prepared without replacement material gained, on average, 17 % increase in strength which became comparable to fly ash replaced mixes as seen in Figure 6. The beneficial effect of fly ash replacement on grout strength at long aging periods was affirmed by several investigators [5-8,13]. Despite the lowest increase with aging time, the highest compressive strengths were still achieved with 20 % marble powder replaced mixes having the same W/C ratio. The maximum strength of 26.97 MPa was achieved with 1.0 W/C ratio mix at this replacement. The reason for the relatively lower increase in the strength with time can be explained by the faster setting and hardening of the marble powder containing mixes, as proved by rheology measurements (Figure 3 and Figure 4). Jiang et al. [13] compared the performances of limestone powder and fly ash in mortars and found that limestone powder accelerated the hydration rate of cement, improved the hydration degree of cement and led to a denser structure due to its filling effect at early age.

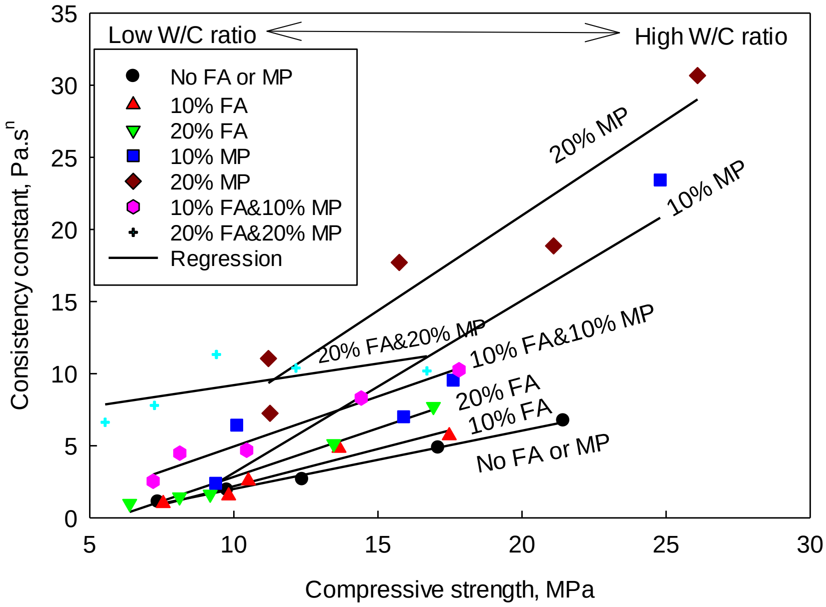

Figure 7. Variation of compressive strength of hardened grouts with consistency coefficient of fresh grout mixes

The relationship between viscosity and strength of the mix was evaluated by plotting the consistency coefficient (a measure of viscosity) versus strength data. For the sake of brevity, only 28 days strength data were plotted and presented in Figure 7. A direct relationship between viscosity and strength was mainly observed for each category. While the marble powder containing fresh mixes were generally more viscous, they became stronger after setting and hardening. It is considered that marble powder decreased flowability by increasing the viscosity, but also prevented bleeding and segregation of cement-aggregate slurries by reacting with unreacted water in the mix. When binary replacements were evaluated, it is seen that the increasing strength with marble powder was almost completely eliminated with fly ash.

4. Conclusions

Fly ash and marble powder were used in grout mix design as partial replacement materials for cement and aggregate, respectively. The following conclusions were drawn:

1. W/C ratio played the key role for grouts in attaining to certain flowability and strength and an inverse relation between flowability and strength was observed for all W/C ratios. The mixes with high W/C ratios were more flowable, but much weaker than the mixes with low W/C ratios. As an example, the compressive strength of 28-day grout decreased from 21.44 MPa to 7.36 MPa when W/C ratio increased from 1.0 to 1.4.

2. Grouts prepared without and with replacing materials exhibited shear thinning behavior, but the replacing materials influenced flow properties differently.

3. The inclusion of fly ash reduced the water demand to obtain flowable mixes but reduced the 28 days strength of grouts by

10-30 % depending on W/C ratio and fly ash amount. The lubricating effect of fly ash particles due to their spherical shape and their relatively larger sizes were considered among the reasons for enhanced flowability and reduced strength.

4. The inclusion of fine marble powder increased the viscosity of fresh and the strength of hardened grout. The highest compressive strength values were obtained with marble powder replaced grouts at given (or fixed) W/C ratios. The reason was mainly explained by filling effect of powders in the mix and increasing total surface area of the ingredients that produced more nucleation sites for cement hydration products, which are responsible for grout strength.

5. The strength of all mixes increased at different levels by increasing aging time from 28 days to 90 days. The highest increase of 24 % and the lowest increase of 5.3 % on average were achieved with 10 % fly ash and 20 % marble powder replaced mixes, respectively. The main reason was explained by the setting and hardening rate (speed) of mixes as supported by rheology results.

Acknowledgements

We acknowledge the financial support of the Scientific Research Projects Unit of Inonu University (Malatya) through project number FBA-2018-920.

Author's Contributions

Hikmet Sis: Supervised the experiment's progress, and drafted and wrote the manuscript.
Tufan Kıyak: Performed experiments, assisted in supplying experimental materials.
Cenk Fenerli: Supplied experimental materials and assisted in performing experiments.
Mehmet Genç: Supplied experimental materials and assisted in performing experiments.

Conflict of interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data Availability Statement

All graphs and data obtained or generated during the investigation appear in the published article.

Ethics

There are no ethical issues with the publication of this manuscript.

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