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Elasticity and Shrinkage of Cement: Sand Mortar Produced in Riyadh

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Abstract. Effects of sand type (white vs red sand) on the stress-strain relationship, modulus of elasticity, and shrinkage of mortar were studied. A total of 108 specimens of 25 × 25 × 275 mm prisms and 98 specimens of 75 × 150 mm cylinders of mortar collected from ongoing construction projects in Riyadh were cast and tested.

It was found that under the same curing conditions and for same mix proportions white sand produces mortar with higher modulus of elasticity and lower drying shrinkage. For instance, replacing 50 or 100% of red sand by white sand increases the modulus of elasticity and reduces the drying shrinkage by more than 50%. This implies that white sand mortar is more stable than red sand one.

1. Introduction

The prime function of mortar is to bond masonry units into a monolithic mass ensuring a watertight wall and providing required structural integrity. It is also used as plastering for architectural finishing. The thicknesses of the mortar for bonding and plastering are standardized to about 10 and 30 mm, respectively. Whereas weak mortar with low modulus of elasticity is desirable to allow for brick or block movement without any conspicuous cracking, strong mortar provides higher bond strength and, consequently, stronger walls when subjected to transverse load[1,2].

The types of mortar generally used in masonry work (for bonding or plastering) are cement: lime:sand, masonry cement:sand, and cement:sand with plasticizer or other additives. The standard mix proportions and other functional requirements for masonry mortar are given in BS 5628[3].

In Riyadh, Saudi Arabia, two types of sand are used in mortar and plastering industry, namely; white silica and red sand. In the last decade the utilization of white sand as a raw material for mortar has tremendously been increased. However, there is no published data to show the properties of concrete or mortar incorporating white silica sand.

This paper presents the results of the experimental work that was carried out on mortar specimens collected from different zones within the Riyadh city. Mortar specimens have been collected which incorporated either red or white silica sand. Tests carried out include stress-strain relationship, modulus of elasticity evaluation, and shrinkage measurements for specimens that were exposed to either water or air curing conditions. The physical and chemical properties of red and white sands used in producing the mortar specimens are also presented.

2. Test Procedure

In this study, Riyadh city was divided into nine different zones and mortar specimens as well as dry materials used were collected from each zone. (Mortar mix proportions) for the collected specimens are shown in Table 1. One hundred and eight 25 × 25× 275 mm shrinkage prisms and ninety eight 75 × 150 mm cylindrical specimens were cast and tested (six shrinkage prisms and three cylindrical specimens were cast at each site, see Table 1. All specimens were cast in the field and subjected to curing at the construction site for the first 24 hours. The next day they were carefully transported to the laboratory, demolded, and labeled. Then the shrinkage specimens were placed in water for 30 minutes, prior to the first initial (zero shrinkage strain) readings. They were then cured in lime saturated water according to ASTM standards C 157-75[9] for 28 days. After the curing period, second initial shrinkage measurements were made and shrinkage specimens of each site were returned back to water tank for water curing conditions and the other three were transferred to the humidity room (26ºC a R.H. 50%) for air curing condition. Shrinkage measurements for each specimen were then carried out at 4th, 7th, 14th day after recording its second initial shrinkage (zero shrinkage strain) reading. The cylindrical specimens, however, were cured by immersing them in lime saturated water for 28 days and tested according to ASTM standard.

TABLE 1. Summary of mix proportions and materials used in mortar preparation at various sites.

Serial no.	Zone and site designation	Mix proportions cements:sand:water	Type of sand
1	Z1S1	1:3:0.7	White
2	Z1S2	1:3:0.79	White
3	Z2S1	1:4:0.98	White
4	Z2S2	1:3:0.65	Red
5	Z3S1	1:4:0.9	White
6	Z3S2	1:3:0.75	White
7	Z4S1	1:3:0.73	White
8	Z4S2	1:1:0.4	White
9	Z5S1	1:3:0.67	White
10	Z5S2	1:3:0.67	White

TABLE 1. Contd.

Serial no.	Zone and site designation	Mix proportions cements:sand:water	Type of sand
11	Z6S1	1:1:0.93	White
12	Z6S2	1:6:0.92	White
13	Z7S1	1:4:0.96	White
14	Z7S2	1:3:0.65	White
15	Z8S1	1:2:0.49	White & red (1:1)
16	Z8S2	1:5:1.0	White & red (1:0.16)
17	Z9S1	1:4:1.05	White
18	Z9S2	1:7:1.45	White

In all the above cases type 1 ordinary portland cement was used.

3. Test Results and Discussion

3.1 Properties of Sand

Red and white sands gradations, specific gravity and absorptivity are shown in Tables 2 and 3. It can be seen from sieve analysis results that the red sand gradation is within the limits of the ASTM C33[4] standard, while white sand is not. Of interest to indicate here that during the analysis process, it was observed that the grain sizes, in both sands, range from pebble to silt ones.

TABLE 2. Typical fine aggregate gradation.

Sieve size (mm)	Red sand % passing	White sand % passing	ASTM-C33 requirement (% passing)
No. 4 (4.75)	100	100	95 - 100
No. 8 (2.36)	82 [8.8]	99.5	80 - 100
No. 16 (1.18)	54.5 [5.5]	97	50 - 85
No. 30 (0.6)	33.3 [3.4]	85.3	25 - 60
No. 50 (0.3)	18.4 [2.2]	42.6	10 - 30
No. 100 (0.15)	7.8 [1.7]	6.6	2 - 10
No. 200 (0.075)		1.0	0 - 3
Pan			

[ ]. Standard deviation for all samples collected.

Results shown in Table 3 manifest that red sand has higher specific gravity and water absorption than white sand. The increase in the specific gravity may be ascribed to the fact that red sand particles are coated by clay and iron oxide. The high value of water absorption of red sand indicates that red sand is more porous than white sand. Thus, it is expected that, for the same workability, red sand mortar requires more mixing water than white sand one.

Table 3. Typical average specific gravity and absorptivity for fine aggregate.

Parameter		Red sand	White sand
Specific gravity			
a.	Bulk dry	2.52 [0.03]	2.51
b.	Bulk saturated	2.57 [0.03]	2.52
c.	Apparent	2.65 [0.03]	2.53
Water absorption		2.03 [0.03]	0.44
Fineness modulus		3.01 [0.03]	1.9

[ ]. Standard deviation for all samples collected.

Microscopic analysis[5] (not shown here), showed that red sand particles are more rounded than that of white sand by 5%. The white sand particles have about 25% sub angular and flaky shape while red sand particles have 20%. Further, it was noticed that some red sand particles were coated with iron oxides. This has been confirmed by chemical analysis (see Table 4). However, for such small differences it can be said that, as far as the particle shape is concerned, there is insignificant difference between both types of sands.

The chemical composition of both types of sand is shown in Table 4. It can be seen that red sand has higher clay, lime and iron contents as indicated by Al_2O_3, CaO and Fe_2O_3, respectively, and lower silica (SiO_2) contents than that of white sand.

Table 4. Typical chemical composition for red and white sands.

Sand	SiO_2	Fe_2O_3	AL_2O_3	TiO_2	CaO	MgO	LoI
Red	82.41	1.96	4.52	0.26	3.56	0.31	7.0
White	99.60	0.03	0.12	0.03	0.06	0.05	0.09

3.2 Compressive and Flexural Strengths

Table 5 presents the test results of compressive and flexural strengths at 3, 7 and 28 days for mortar incorporating different types of sands. As expected, the compressive and flexural strength increases with age. However, there is a large variation in strength from batch to batch and from one site to another. This is attributed to the fact that, in most cases, mix proportions and water/cement (w/c) ratio are different. They are mostly specified by unskilled masons. Moreover, during the collection of specimens from different construction sites, it was noticed that there was no uniform supervision in any of the sites and there was no compliance with any specifications or standards. Actually, laborers added water, even after two hours from the start of mixing, based only on their judgment for the required workability.

Results of compressive and flexural strengths for mortar incorporating red or white sand show, as expected, a decreasing strength with increasing w/c ratio. It can be seen that there is a sharp decrease in strength associated with the increase in the sand and water content, and the decrease in cement content as shown by specimens Z2S1, Z3S1, Z6S1, Z6S2 and Z8S2. As the only controlling factor in selecting the mix proportions (in view of the masons) is workability, it can be easily seen in Table 1 that the quantity of water needed is directly related to the sand content which is also specified by the masons. Thus, at different sites even when the same ratio of sand to cement was used, the quantity of water added was in most cases different. Thus, it was not surprising to get mortar with the same cement to sand ratio and yet with different strength. This is confirmed by comparing the test results of specimens Z3S1 vs Z7S1 and Z3S2 vs Z7S2 in Tables 1 and 5.

TABLE 5. Compressive and flexural strengths of mortar specimens collected from different sites.

Designation no.	Age day	Compressive strength (MPa)	Flexural strength (MPa)	Designation no.	Age day	Compressive strength (MPa)	Flexural strength (MPa)
Z1S1	3 7 28	13.4 18.6 29.8	4.9 5.5 7.4	Z6S1	3 7 28	3.9 5.2 8.5	1.6 2.1 3.3
Z1S2	3 7 28	10.9 14.8 26.3	3.4 4.5 6.1	Z6S2	3 7 28	4.2 5.4 10.7	2.1 2.7 4.2
Z2S1	3 7 28	5.3 8.4 13.3	1.9 2.4 4.3	Z7S1	3 7 28	5.3 8.7 15.6	1.6 3.5 4.9
Z2S2	3 7 28	20.9 21.5 31.5	4.6 5.3 7.2	Z7S2	3 7 28	13.8 21.3 25	4.9 5.4 6.8
Z3S1	3 7 28	8.3 10.2 20.1	2.2 3.4 5.1	Z8S1	3 7 28	18.4 30.2 40.6	6.2 7.2 8.9
Z3S2	3 7 28	11.3 16.5 30.9	3.6 5.3 7.4	Z8S2	3 7 28	4.5 7.2 10.8	2.1 2.3 3.7
Z4S1	3 7 28	13.6 17.4 24.9	3.5 4.9 6.4	Z9S1	3 7 28	5.6 7.1 8.2	1.3 1.6 1.8
Z4S2	3 7 28	22.2 37.4 44.3	5.6 7.9 9.9	Z9S2	3 7 28	1.6 2.2 4.6	0.7 1.1 1.5
Z5S1	3 7 28	14.5 20.3 21.9	3.7 4.4 5.5				
Z5S2	3 7 28	14.9 20.0 25.96	3.9 4.7 5.6				

To compare the compressive and flexural strengths at 28 days (see Table 5) of both red and white sand mortars with equal mix proportions, examine results of specimens Z2S2 (red sand) and Z7S2 (white sand) where mix proportions (cement:sand:water) for both of them were (1:3:0.65) by volume. It is found that the red sand produces mortar with higher strength than that of white sand. However, for 7 days results, the strengths were equal. On the other hand, the modulus of elasticity for the white sand mortar is higher than that of the red sand mortar (see results of specimens Z2S2 and Z7S2). This finding contradicts the well documented test results that regardless of the sand type, the modulus of elasticity increases with the increase in the ultimate compressive strength of the mortar, f^{l}_{cm}. Thus, a firm conclusion on the strength properties of red and white sand cannot be reached at this stage.

Results shown in Tables 1 and 5 also show that when the cement to sand ratio was reduced to 1, the ultimate compressive strength, f^{l}_{cm} of the mortar increased (see for example, results of specimen Z4S2). However, this implies a more expensive mortar. Another alternative to improve f^{l}_{cm} which is less expensive seems to be achieved by reducing the sand to cement ratio to 2 and replacing 50% of the white sand by red sand (see test results for specimen Z8S1). Such reduction in the quantity of the total sand and 50% replacement by red sand increase the 28-day f^{l}_{cm} of specimen Z8S1 over that of Z3S2 (both specimens had almost the same consistency as measured by the flow table test) by more than 30%.

Fig. 1 presents the relationship between the compressive and flexural strengths when all specimens i.e. combined white and red sand samples, were considered. However, based on the statistical analysis the relationship (considering all samples) can be expressed as:

$$f^{l}_{tm} = 0.25\ f^{l}_{cm} \tag{1}$$

Where f^{l}_{tm} is the modulus of rupture of the mortar in Mpa, and

f^{l}_{cm} is the ultimate compressive strength of the mortar in MPa.

3.3 Stress-strain Behavior of Mortar

Typical stress-strain behavior for mortar under compression is shown in Fig. 2. The secant modulus of elasticity, E, for all mortar specimens at 40% ultimate stress, as recommended by the ASTM C469[6] standard are presented in Table 6. For the sake of comparing the results, the predicted moduli of elasticity using the ACI[7] and BS[8] formulas are also shown in the same Table.

The results show that, (for specimens with identical mix proportions) mortar incorporating white sand has a higher modulus of elasticity and is more brittle than its counterpart of the red sand mortar. For instance, the average modulus of elasticity for specimen Z7S2 (containing white sand) is 54% higher than that of specimen Z2S2 (containing red sand). The same trend also exists for specimens from other zones. Replacement of 50% of red sand by the same amount of white sand increases the modulus of elasticity by 58% (See Tables 1 and 6, specimens Z2S2 and Z8S1). Thus (under the same mixing

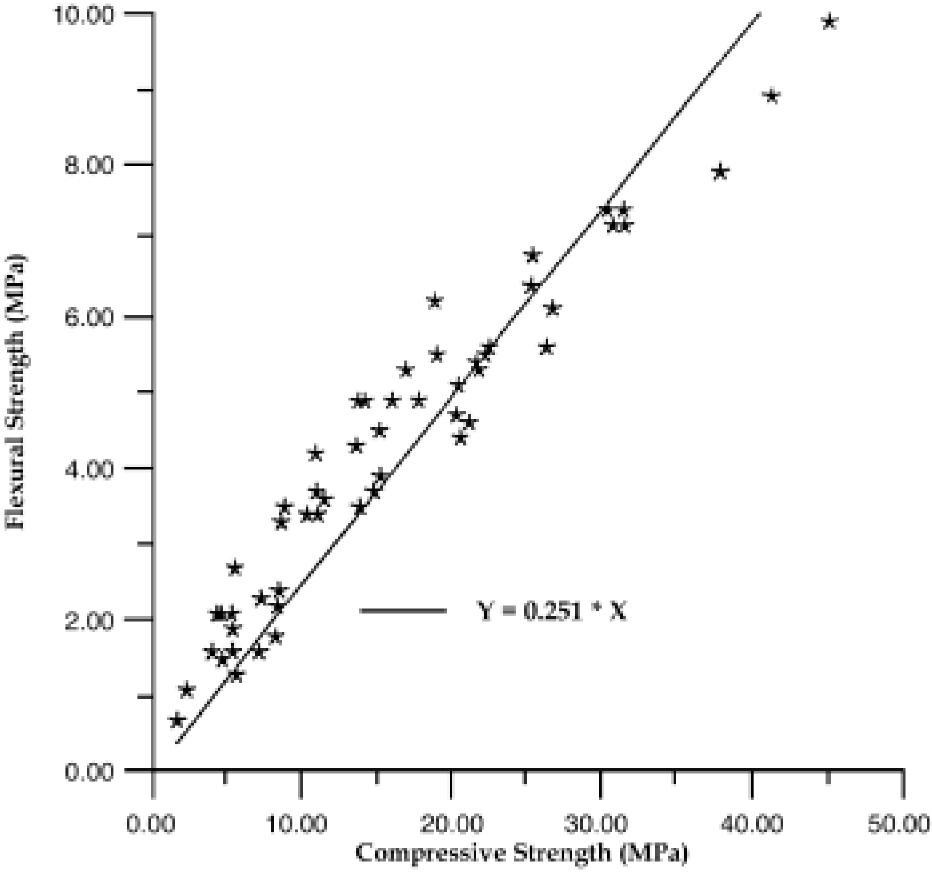

FIG. 1. Relationship between flexural strength and compressive strength for mortar specimens (all specimens, combined white and red sand samples).

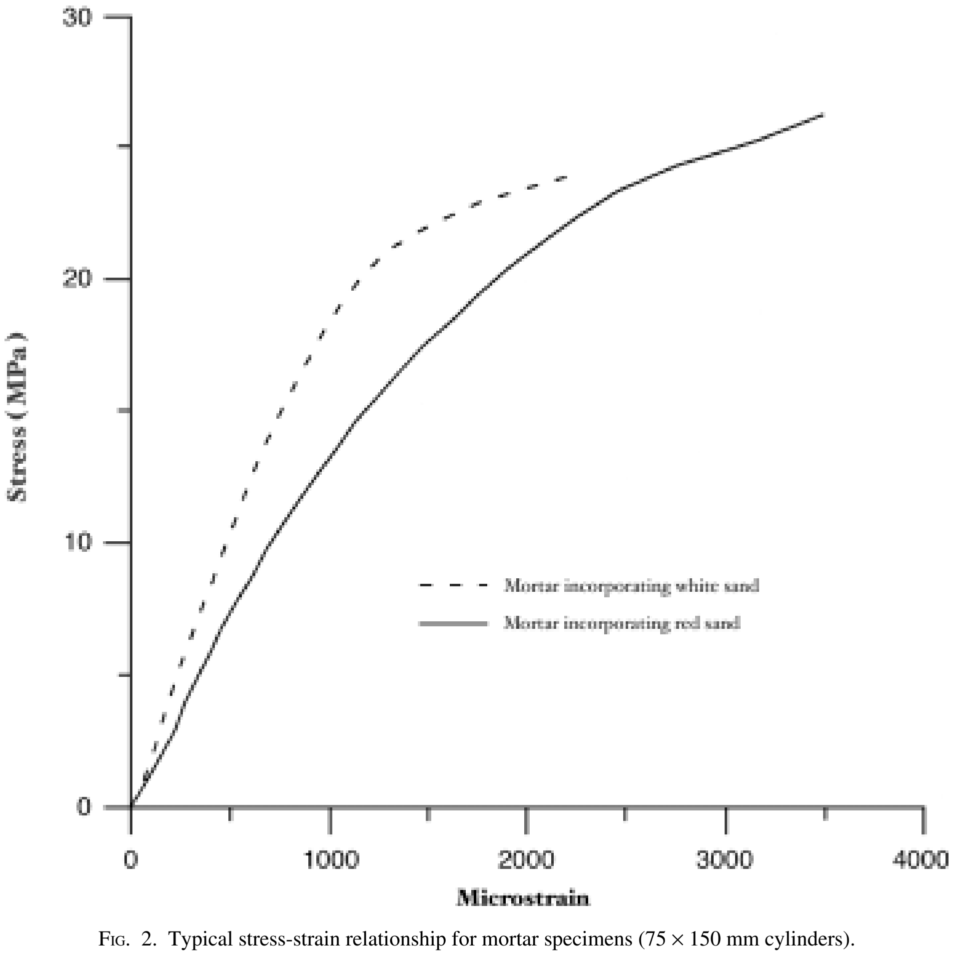

FIG. 2. Typical stress-strain relationship for mortar specimens (75 × 150 mm cylinders).

and curing conditions) it is expected that mortar which contains white sand is more stable than that which contains red sand.

TABLE 6. Modulus of elasticity of mortar specimens collected from different construction sites.

Specimen no.	Age day	Modulus of elasticity, GPa		Specimen no.	Age day	Modulus of elasticity, GPa	
		Measured	Predicted			Measured	Predicted
Z1S1	3 7 28	– – 23.4	25.9* (27.6)**	Z6S1	3 7 28	– – 11.9	13.8 (18.2)
Z1S2	3 7 28	– – 19.0	24.3 (26.5)	Z6S2	3 7 28	– – 19.8	15.5 (19.7)
Z2S1	3 7 28	– – 9.6	17.3 (21.1)	Z7S1	3 7 28	– – 21.3	18.7 (22.3)
Z2S2	3 7 28	– – 13.95	26.4 (27.9)	Z7S2	3 7 28	– – 21.5	23.7 (26)
Z3S1	3 7 28	– – 15.9	21.3 (24.2)	Z8S1	3 7 28	– – 22.1	30.2 (30.5)
Z3S2	3 7 28	– – 22.3	26.4 (27.9)	Z8S2	3 7 28	– – 16.2	15.6 (19.7)
Z4S1	3 7 28	– – 19.7	23.7 (26.0)	Z9S1	3 7 28	– – Weak	13.6 (18)
Z4S2	3 7 28	– – 27.2	31.5 (31.4)	Z9S2	3 7 28	– – Weak	10.7 (14.9)
Z5S1	3 7 28	– – 20.9	22.2 (24.9)				
Z5S2	3 7 28	– – 20.5	24.2 (26.4)				

$^{*}E = 43\,\rho^{1.5} \times 10^{-6}$ ACI formula
$^{**}(\ )\ E = 1.7\,\rho^{2} f'_{cm}{}^{0.33} \times 10^{-6}$ BS formula

Results in Table 6 also indicate that neither the ACI nor the BS formulas reasonably estimated the measured moduli of elasticity. Although the deviation may be attributed to many reasons, different sand types, quality control and absence of enforcement of specific standard are definitely among those reasons.

Figure 3 shows the average relationship between the modulus of elasticity and the ultimate compressive strength for mortar specimens. Thus, for combined white and red sand mortar samples, the relationship can be expressed as:

$$E_m = 720 f^l_{cm} \tag{2}$$

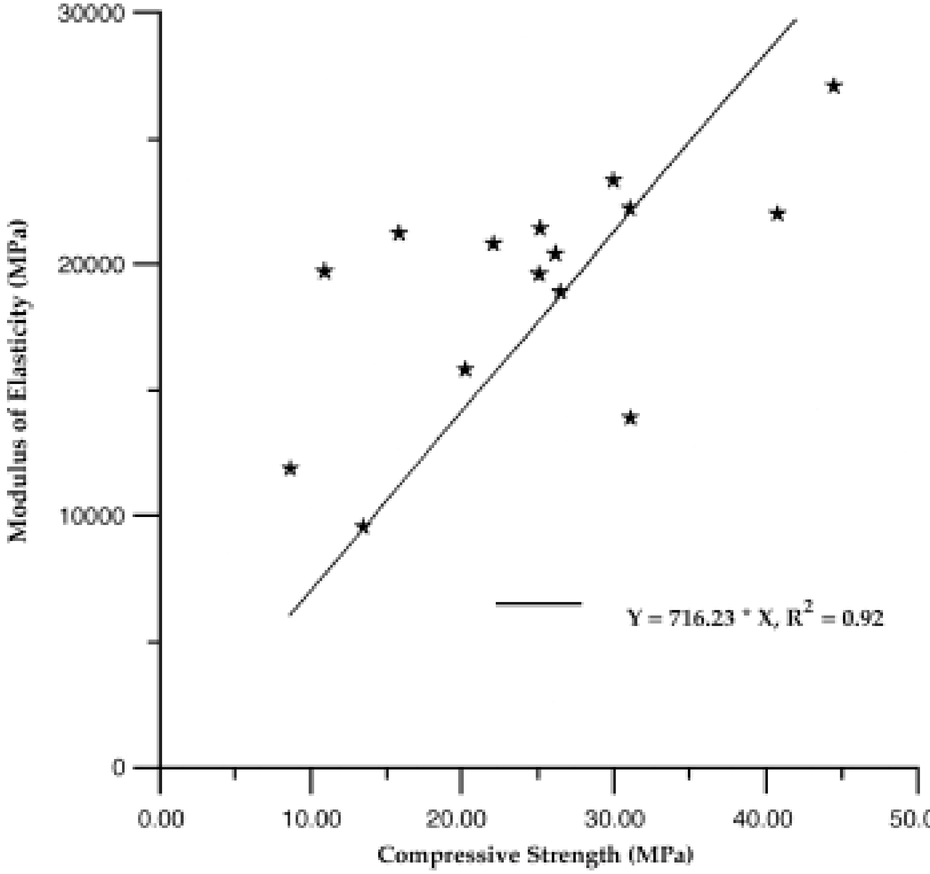

FIG. 3. Relationship between modulus of elasticity and compressive strength for mortar specimens (All specimens: combined white and red sands samples).

3.4 Shrinkage of Mortar

Figure 4 shows the effect of sand type on the shrinkage of mortar. The mix proportions for specimens Z2S2 (red sand) and Z7S2 (white sand) were 1:3:0.65 (cement:sand:water). Results show that under air or water curing conditions, specimen Z2S2, experienced higher rate and larger shrinkage. This implies that under the same curing condition and mix proportions, specimen containing white sand mortar shrinks at a lesser rate and by a smaller magnitude than that of the red sand mortar.

After 224 days of air exposure, specimen Z2S2 (containing red sand mortar) shrank by1122 microstrain. The corresponding shrinkage for specimen Z7S2 (containing white

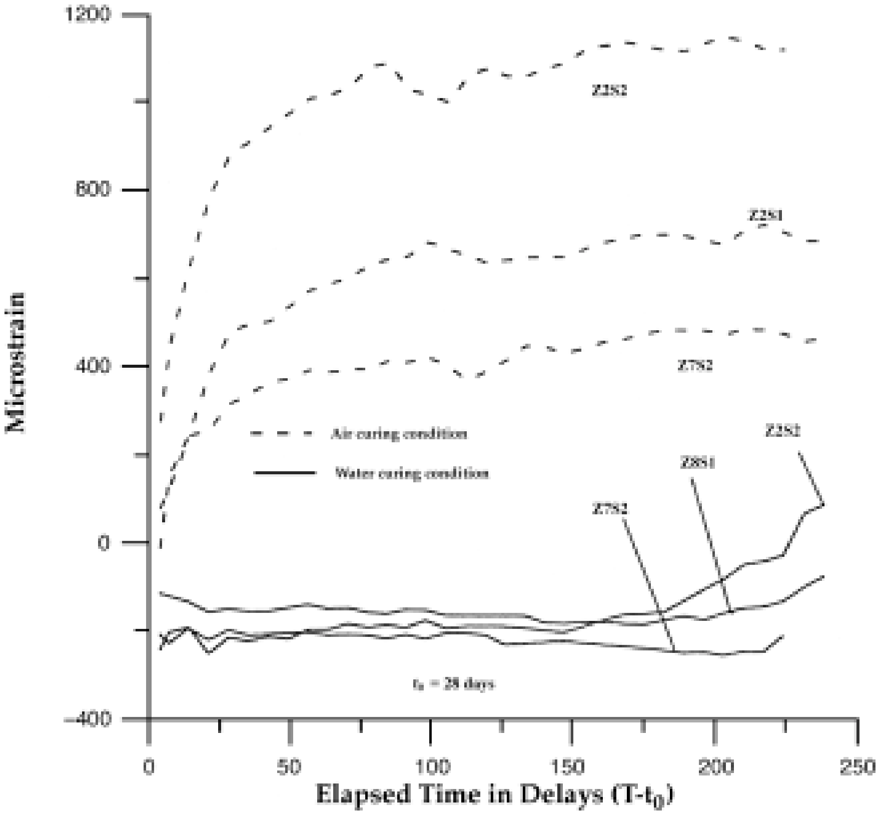

FIG. 4. Effect of sand type (white vs red) on the shrinkage of specimens Z2S2 and Z1S1.

sand mortar) was 477 microstrain. Thus, shrinkage of specimen Z7S2 reduced by about 60% due to the replacement of red sand by white sand. The corresponding reduction in swelling of the counterpart specimens when subjected to water curing condition was 87%. On the other hand, the corresponding shrinkage for specimen Z8S1 (mix proportions cement:sand:water were 1:2:0.49 and fine aggregate was composed of 50% red sand and 50% white sand) was 708 microstrain which is 59% less than that of specimen Z2S2. Again, the main cause of such reduction may be attributed to the 50% replacement of the red sand by white sand. Furthermore, red sand has higher specific gravity and water absorption due to the presence of clay, lime and iron oxide as deleterious substances which contribute to more shrinkage. Thus reducing red sand content will reduce the shrinkage of mortar specimens.

To provide a general view of the shrinkage measurements that were carried out, Table 7 presents the average shrinkage results of specimens Z6S1, Z7S1, and Z8S2.

Average magnitude of shrinkage occurring by the 224th day after recording the initial shrinkage measurement for all specimens are presented in Table 8. The 224th day was selected because it was attained by all specimens. Results shown in this table do not have any specific trend and, therefore, solid conclusion can not be drawn on the basis of these results.

TABLE 7. Typical shrinkage results for specimens Z6S1, Z7S1, and Z8S2 (in microstrain).

Z6S1			Z7S1			Z8S2		
Days	Water curing	Air curing	Days	Water curing	Air curing	Days	Water curing	Air curing
4	– 88	39	4	– 161	20	4	– 200	– 16
7	– 68	141	7	– 163	48	7	– 194	82
14	– 42	398	14	– 121	204	14	– 205	261
21	– 34	302	21	– 151	160	21	– 226	241
28	– 78	287	28	– 165	251	28	– 217	290
35	– 66	291	35	– 162	295	35	– 211	354
42	– 77	473	42	– 152	286	42	– 216	410
49	– 69	487	49	– 157	282	49	–	–
56	– 78	471	56	– 157	270	56	– 207	451
63	– 14	494	63	– 124	251	63	– 194	497
70	– 1	525	70	– 115	343	70	– 197	503
77	50	535	77	– 114	350	77	– 188	533
84	84	553	84	– 100	384	84	– 198	549
91	77	568	91	– 116	395	91	– 198	551
98	86	560	98	– 121	395	98	– 176	586
105	83	608	105	– 100	413	105	– 193	568
112	71	–	112	– 115	337	112	– 185	582
119	63	577	119	– 108	387	119	– 183	611
126	80	585	129	– 99	411	126	– 178	600
133	84	592	133	– 97	409	133	– 176	606
140	80	610	140	– 97	413	140	– 179	613
147	62	595	147	– 103	413	147	– 179	624
154	87	606	154	– 111	408	154	– 128	635
161	87	606	161	– 105	404	161	– 105	666
168	91	605	168	– 85	431	168	– 57	671
175	72	614	175	– 79	433	175	– 48	675
182	90	621	182	– 78	445	182	–	–
189	88	626	189	–	457	189	3	666
196	87	631	196	– 48	–	196	158	657
203	84	635	203	2.9	457	203	173	666
210	82	624	210	17	426	210	241	700
217	93	641	217	31	445	217	306	705
224	112	651	224	64	457	224	354	705
231	157	647	231	99	451	231	416	704
238	197	637	238	136	445	–	–	–
245	229	644	245	140	446	–	–	–

TABLE 8. Average ultimate shrinkage values after 224 days of exposure for specimens from all sites (in microstrain).

Spec. design.	Water curing	Air curing
Z1S1	62	715
Z1S2	– 117	598
Z2S1	290	828
Z2S2	– 210	1121
Z3S1	– 24	860
Z3S2	– 20	696
Z4S1	– 91	714
Z4S2	277	442
Z5S1	– 71	466
Z5S2	– 91	490
Z6S1	112	651
Z6S2	303	568
Z7S1	64	89
Z7S2	– 26	457
Z8S1	– 131	707
Z8S2	354	705
Z9S1	376	400
Z9S2	68	735

Conclusions

Based on the survey, results obtained from the construction sites and field and laboratory tests, the following conclusions were drawn:

1. White sand particles are not well graded. The sand grading curve does not confirm with the ASTM C-33 limits.
2. White sand has lower specific gravity and water absorption than the red sand.
3. Flexural strength of mortar prisms made using white sand mortar is about 0.25 times its ultimate compressive strength.
4. Modulus of elasticity of combined white and red sand mortar is about 720 times its ultimate compressive strength.
5. Mortar incorporating white sand has lesser rate and smaller shrinkage magnitude than that which incorporates red sand. Replacement of 50 or 100% of red sand by the same amount of white sand reduces the drying shrinkage and increases the modulus of elasticity by more than 50%. However, due to limited number of red sand samples, further research is needed to confirm this conclusion.

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معامـل المرونـة والإنكمـاش للمـلاط الأسمنتي المستخـدم بمديـنة الريـاض

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المستخلص . تمت دراسة خواص معامل المرونة والإنكماش للمـلاط الأسـمنتي بمدينـة الريـاض باستـخـدام الرمـل الأبيض والأحـمـر ، وقد تم أخـذ عدة عينـات من المـلاط المستخـدم من مواقـع مشاريـع متعـددة تحت التنفـيـذ بمدينــة الريـاض كـانت عـبارة عن ١٠٨ عـينـة مخـروطية (٢٥×٢٥×٢٧٥مم) و٩٨ عينة اسطوانية (٥٧×١٥٠مم) .

وجد عند استخدام طريقة معالجة ونسبة خلطة واحدة أن الملاط الذي أُنتج باستخدام الرمل الأبيض أكثر مرونة وأقل إنكماشًا من الملاط المنتج باستخدام الرمل الأحمر بمقدار ٥٠٪ . ويستنتج من ذلك أن الملاط المنتج باستخدام الرمل الأبيض أكثر ثباتًا من الملاط المنتج بالرمل الأحمر .