Pergamon

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Cement and Concrete Research 33 (2003) 815–822

CEMENT AND CONCRETE RESEARCH

Properties of heavyweight concrete produced with barite

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Received 6 December 2001; accepted 21 November 2002

Abstract

Heavyweight concrete has been used for the prevention of seepage from radioactive structures due to the harmful effect of radioactive rays to living bodies (i.e., carcinogenic, etc.). The most important point about heavyweight concrete is the determination of w/c ratio. Selected cement dosage should be both high enough to allow for radioactive impermeability and low enough to prevent splits originating from shrinkage. In this study, heavyweight concrete mixtures at different w/c ratios were prepared in order to determine the most favorable w/c ratio of heavyweight concrete produced with barite. Physical and mechanical experiments were first carried out, and then by comparison with the results of other related studies the findings of this study were obtained. At the end of the study, it was found that the most favorable w/c ratio for heavyweight concrete is 0.40 and the cement dosage should not be lower than 350 kg/m^3.

Keywords: Barite; Heavyweight concrete; Mechanical properties

1. Introduction

Heavyweight concrete has been widely used to protect against radioactive rays in nuclear power plants, medical units, and in structures where radioactive impermeability is required. Heavyweight concrete absorbs the energy of neutrons via its contents, and for this reason, heavyweight concrete can be used as a perfect protective material. Neutrons have a significant role in atomic reactors in that they are particles having no electric charge, high energy, and the property of great penetration. Neutron reaction upon the material does not always vary with the atomic number of each material, which is a different situation with γ-rays. At the same time, absorption occurs by the realization of secondary γ-rays and the abundance and energy of these rays varies from one material to another. For this reason, a reactor shield should be selected after considering the dominating properties of that reactor [1]. In general, the strength of the shield against radiation penetration has a direct relationship to the thickness of the shield. The most difficult problem to consider when designing a shield is fast neutrons [2,3]. The compressive strength is not a predominant factor because of the thickness of the radiation shields and the use of high-quality concrete in the mixtures. Furthermore, the average shrinkage of heavyweight concrete is 30% higher than that of conventional concrete. In accordance with code Turkish Code (TS) 3440, conventional concrete should be durable against harmful water, fluids, and gases [4]. However, there is no such necessity in heavyweight concrete, only in those used as protectors against radiation [5].

Specific gravities of heavyweight concrete aggregates are usually more than 4000 kg/m^3. Barite is the most common aggregate used for heavyweight concrete. Heavyweight concrete produced with barite has 1.25 meV of γ-ray absorption capacity. These are formulated as $\mu = 0.055e^{1.36c}$ cm^{-1} (c is barite percent in aggregate) according to the ratio of barite aggregate used in the aggregate and also the concrete unit weight $\mu = 0.006e^{1.04\Delta}$ cm^{-1} (Δ is concrete unit weight, kg/dm^3) [6]. Moreover, the thermal expansion coefficient of this concrete is double that previously mentioned and thermal conductivity is lower than in normal concrete. Barite aggregates obtained from the Konya–Beyşehir–Höyük region were used in this study. This deposit has 12,700,000 tons of high-quality barite reserves. Using barite found widely and abundantly in Turkey for the production of heavyweight concrete would be beneficial for many reasons.

2. Experimental study

The experimental study of heavyweight concretes produced with barite is described in this section. Information about physical and mechanical experiments on heavyweight

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0008-8846/02/$ – see front matter
doi:10.1016/S0008-8846(02)01063-3

Table 1
Physical properties of barite

Aggregate size (mm)	Loose unit weight (kg/m^3)	Dry unit weight (kg/m^3)	Saturated unit weight (kg/m^3)	Water absorption % for 48 h
Coarse (>4)	2235	4002	4011	0.002
Fine (<4)	2210	3946	3988	0.010

concrete is also provided. The physical, mechanical, and petrographic structure of the barite mineral that is used in heavyweight concrete production was examined with seven different w/c ratios and two different cements used in experiments. At the end of the experiments, the appropriate w/c ratio and cement dosage for heavyweight concretes were obtained.

2.1. Properties of aggregates

2.1.1. Barite

Barite was first used as a filling substance in white dye production. In Turkey, barite mining showed development after 1964 with barite sources existing in many cities. The classified maximum grain size of barite is 16 mm, with this classification appropriated by TS 1226 [7] and TS 1227 [8] fine sieve order that was further appropriated to TS 706 [9] in the laboratory. The fine and coarse parts of aggregates, classified according to their grain size, loose unit weight, saturated and dry unit weight, and the water absorption properties of barite (given in Table 1) were determined appropriate to TS 3526 [10] and TS 3529 [11]. Aggregates used were the following: (a) 12% for 0.50–1 mm, (b) 18% for 1–2 mm, (c) 20% for 2–4 mm, (d) 20% for 4–8 mm, and (e) 30% for 8–16 mm grain sizes. The Grading Curve of Aggregates is given in Fig. 1.

The petrographic and mechanical properties of aggregate was established in the petrography laboratory of the Geology Department of Osmangazi University. Thin sections of barite specimens selected from aggregates were examined under a petrographic microscope. No mineral other than barite was observed on the thin sections. Barite crystals show dimensions that range between 25 and 1200 μm. The mechanical properties of barite were found through experiments on core specimens with ∅ of 7.5 × 15 mm. Additionally, 36.8 MPa of compressive strength was observed in mechanical experiments done on barite specimens prepared from given core dimensions.

Table 2
Amounts of heavyweight concrete composition

W/c ratio	Amount of water (kg/m^3)	Amount of cement (kg/m^3)	Amount of aggregate (kg/m^3)	Absorbed water (kg/m^3)	Slump (cm)
0.30	105	350	3038	24.30	0.5
0.35	123	350	2967	23.70	1.0
0.40	140	350	2876	23.00	1.5–2
0.45	158	350	2835	22.65	2.5
0.50	175	350	2756	22.00	4–5
0.55	193	350	2683	21.46	6–7
0.60	210	350	2615	20.92	7.0

2.2. Components and production of heavyweight concretes

Cylindrical standard specimens with Φ of 15 × 30 cm were used in experiments. Three cylindrical specimens were cast for each w/c ratio. These were installed in three steps during the filling of concrete specimens and at each step were vibrated on shaking tables. The specimens were then kept in a 20 °C curing room having 98% relative humidity for 24 h after which they were preserved for 27 days in lime-saturated water [13]. The absolute volume method was used in the calculation of the concrete mixture [12]. Cement dosage was accepted as constant at 350 kg/m^3 because this dosage is the most common in application for the determination of components.

2.3. Physical and mechanical properties of heavyweight concrete

PKC 32.5 (blended cement, Type II, specific gravity 2850 kg/m^3 with the Blain surface area being 3574 cm^2/g) and PC 42.5 (Type III, specific gravity 3100 kg/m^3 with the Blain surface area being 3182 cm^2/g) cement types were used and the amounts of mixture components used for the concrete specimens prepared at seven different w/c ratios are shown in Table 2. The ultrasound duration,

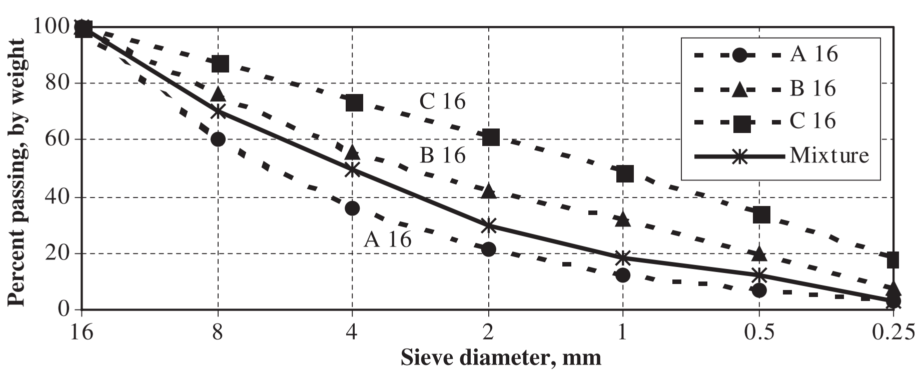

Fig. 1. Grading curve of aggregates.

Table 3
Results of physical and mechanical experiments of produced heavyweight concretes

Cement type	W/c ratio	Unit weight (kg/m^3)	Resonance frequency (kHz)	Ultrasound duration (μs)	Schmidt hardness	Compressive strength (MPa)
PKC 32.5	0.30	3288	3.08	68.9	36	31.8
	0.35	3280	3.10	69.1	34	31.1
	0.40	3272	3.10	68.2	34	31.2
	0.45	3247	3.09	69.4	35	29.2
	0.50	3227	3.13	70.5	35	28.6
	0.55	3220	3.14	70.8	33	27.6
	0.60	3203	3.14	70.6	33	26.0
PC 42.5	0.30	3359	3.10	69.1	44	40.1
	0.35	3356	3.11	69.5	43	39.4
	0.40	3346	3.11	69.5	42	42.6
	0.45	3322	3.13	69.9	40	35.9
	0.50	3309	3.15	70.8	40	35.6
	0.55	3296	3.15	71.0	39	33.8
	0.60	3278	3.16	71.2	39	32.5

Table 4
Regression equations and correlation coefficients of relations

Cement type	*a*	*b*	*c*	R^2
Slump (cm)				
PKC 32.5	38.095	– 9.825	– 0.4167	.9887
PC 42.5	45.328	– 18.1214	1.869	.9471
Compressive strength (MPa)				
PKC 32.5	– 34.286	11.571	37.436	.9743
PC 42.5	– 72.381	35.857	36.374	.4255
Ultrasound duration (μs)				
PKC 32.5	– 13	0.2143	3.0366	.9454
PC 42.5	0.2381	– 0.007	3.064	.7257
Resonance frequency (kHz)				
PKC 32.5	– 18.095	– 8.5714	69.655	.9528
PC 42.5	4.7619	3.2857	67.652	.8230
Schmidt hardness				
PKC 32.5	27.619	– 30.143	42.038	.7821
PC 42.5	33.333	– 48.295	53.654	.9930

resonance frequency, and Schmidt hardness experiments used for nondestructive concrete experiments were carried out. The results of these experiments are given in Table 3. *E* modulus values were calculated from ultrasound duration values. The σ–ε curve, which is dependent on calculations measured from the compression tests of heavyweight concretes' prepared cylindrical specimens, will be given later.

3. Evaluation of results

In this study, through experimentation, the physical and mechanical properties of heavyweight concrete were investigated. The barite unit weight of approximately 4000 kg/m^3 found in physical experiments is the desired value for heavyweight concrete production. The compressive strength obtained in mechanical experiments reveals sufficient values for aggregates by using barite as an aggregate in concretes. The unit weight of produced concretes was 3203–3288 kg/m^3 at PKC 32.5 and was 3278–3359 kg/m^3 at PC 42.5. Unit weight of heavyweight concrete was 25% higher than the unit weight of normal concrete. As shown in Fig. 2, slump increased when the w/c ratio increased. There is not very much difference in terms of slump for both cement types. Slumps were not high enough without the use of plasticizer. With the addition of plasticizer, the workability of the concrete improved. In Fig. 2, the second-degree equation of drawn graphics was found as $y = ax^2 + bx + c$. *a*, *b*, and *c* values and correlation coefficients for both cement types are given in Table 4. Fig. 3 shows the variation of compressive

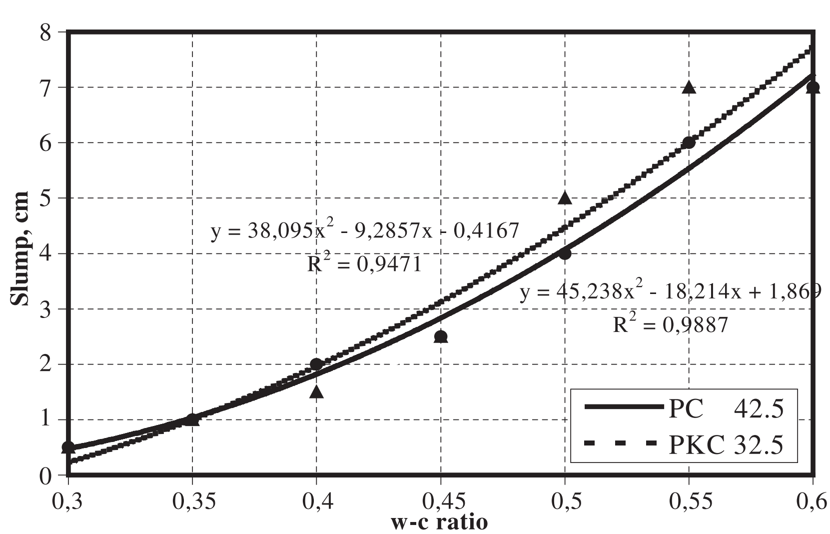

Fig. 2. Variation of slump by w/c ratio.

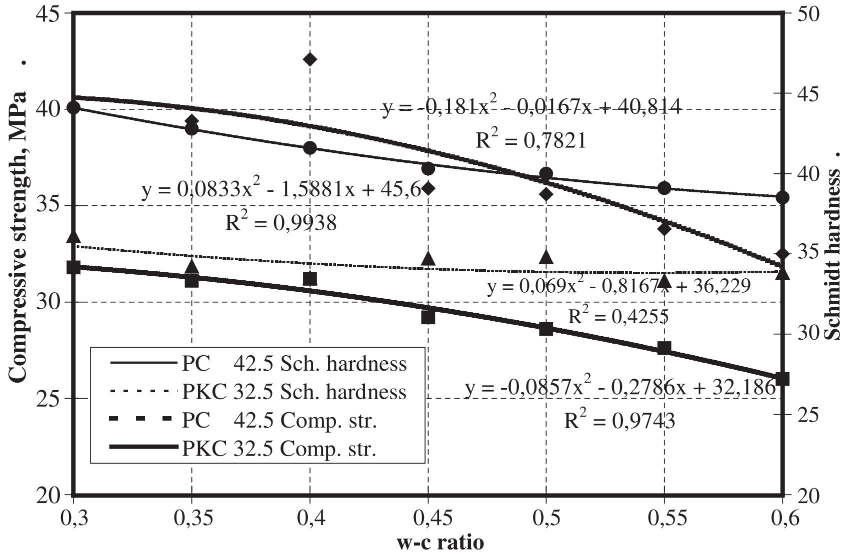

Fig. 3. Variation of compressive strength and Schmidt hardness by w/c ratio.

strength and Schmidt hardness values for selected w/c ratios. Theoretically, the w/c ratio is proposed as 0.30–0.50 for heavyweight concretes. It was observed that when the w/c ratio increased, the compressive strength decreased. Another important consideration whenever high compressive strength is desired is the obtaining of correct workability according to the selected w/c ratio. To this aim, it can be said that heavyweight concretes obtained from PC 42.5 and PKC 32.5 and from 0.40 w/c ratios have properties of high compressive strength and appropriate workability. The highest strength for concretes obtained from PC 42.5 is obtained as 42.6 MPa at 0.40 w/c ratios. The property coefficients of the second-degree equations for PKC 32.5 and PC 42.5 for the values used in Figs. 2–4 can be seen in Table 4.

In order to obtain information on the hardness of concretes, the Schmidt hardness experiment was applied to heavyweight concretes produced at seven different w/c ratios, using PKC 32.5 and PC 42.5 cement. As seen in Fig. 3 while the w/c ratio increases, compressive strength and, consequently by direct relation, Schmidt hardness decreases. The reason behind the use of the Schmidt hammer in this study is the high compressive strength of the specimens. Much more sensitive results concerning the hardness of concrete were gained from the minor differences of impressions of impact on the concretes. As seen in Fig. 4, when the w/c ratio increased, resonance frequency values also increased. A similar situation also exists in ultrasound duration. As the w/c ratio increases, because of increased voids of concrete, ultrasound duration also increases. The w/c ratio vs. the E modulus variation is given in Fig. 5. The E modulus obtained from σ–ε curve is given in Figs. 6 and 7, and the E modulus obtained from the ultrasound duration

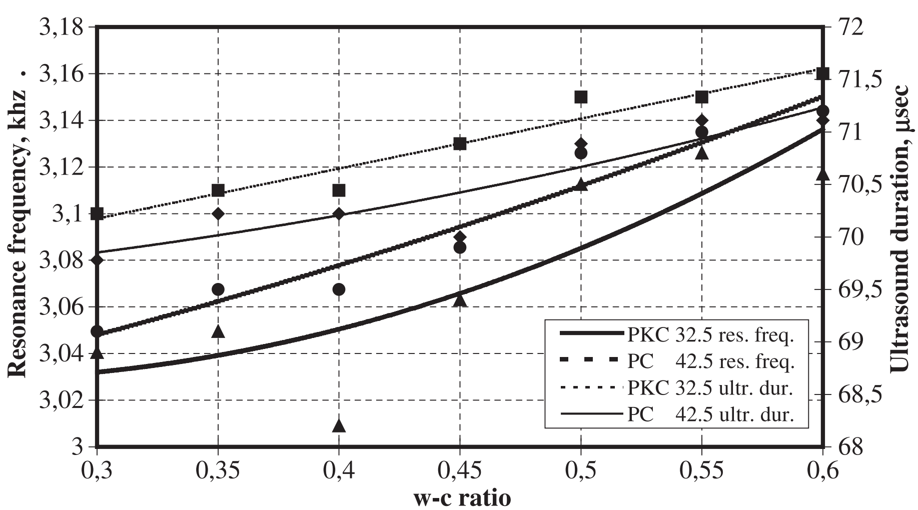

Fig. 4. Variation of ultrasound duration and resonance frequency by w/c ratio.

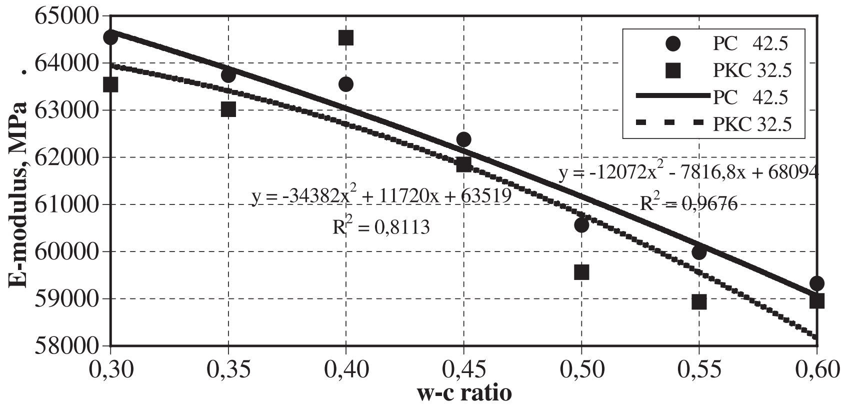

Fig. 5. Variation of heavyweight concrete's *E* modulus by w/c ratio.

experiment is shown in the same figure. If we denote the *E* modulus from the σ–ε curve as E_{din} and the *E* modulus obtained by the ultrasound test as E_v, then according to the observations, we can say that $E_v > E_{din}$. According to the observations, E_v is 8% higher than E_{din}. Voellmy relates E_v as higher than E_{din} due to water in the voids under very small tensions, and this plays a positive role in this method [14]. The *E* modulus obtained from σ–ε curve reaches approximately 7–13% higher values than *E* modulus obtained from the ultrasound test. The *E* modulus of concretes produced by PC 42.5 reaches 3–5% higher values than those of PKC 32.5.

4. Discussion of results

The major aim of this study is to examine the physical and mechanical properties of heavyweight concrete produced with barite. During this study, the radioactive impermeability property of heavyweight concretes was also evaluated. A cement dosage not exceeding 350 kg/m^3 is proposed for this aim in heavyweight concretes [15]. In another study, it is proposed that the cement dosage should be greater than 350 kg/m^3. In this case, the coarse aggregates have a tendency to disturb the mixture homogeneity. In order to solve this problem, increasing the amount of fine aggregates is proposed. This improves the characteristics of the mixture by high-bonded water [16]. However, while increasing the cement dosage in order to improve shielding property, the risk of increased shrinkage should be borne in mind. Moreover, the cracks formed due to shrinkage are the most undesirable situation to occur in nuclear power plants where the probability of radioactive seepage from these cracks is quite high. Therefore, the unit weight of concretes in physical experiments being applied to specimens with a dosage of 350 kg/m^3 and of seven different w/c ratios by the usage of two different cement types is sufficient in weight for providing radioactive impermeability. Generally, a 3203-

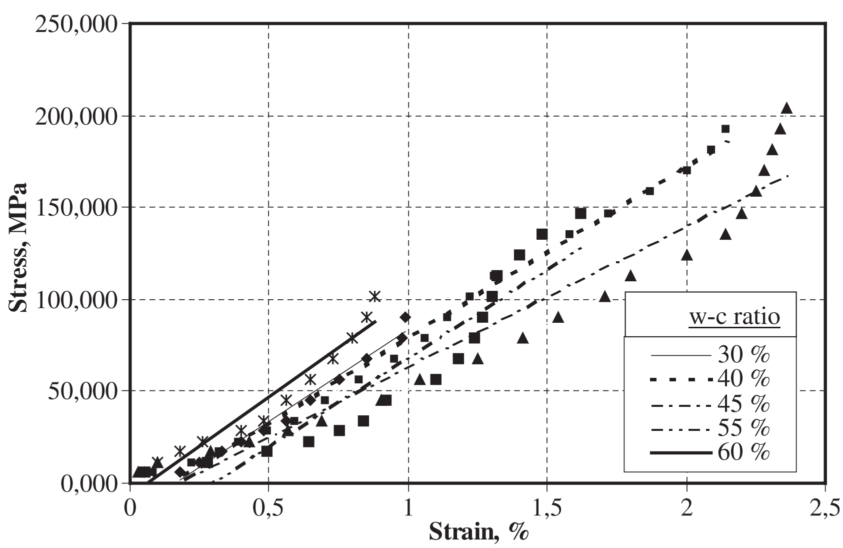

Fig. 6. Stress–strain relationship of concrete with PKC 32.5.

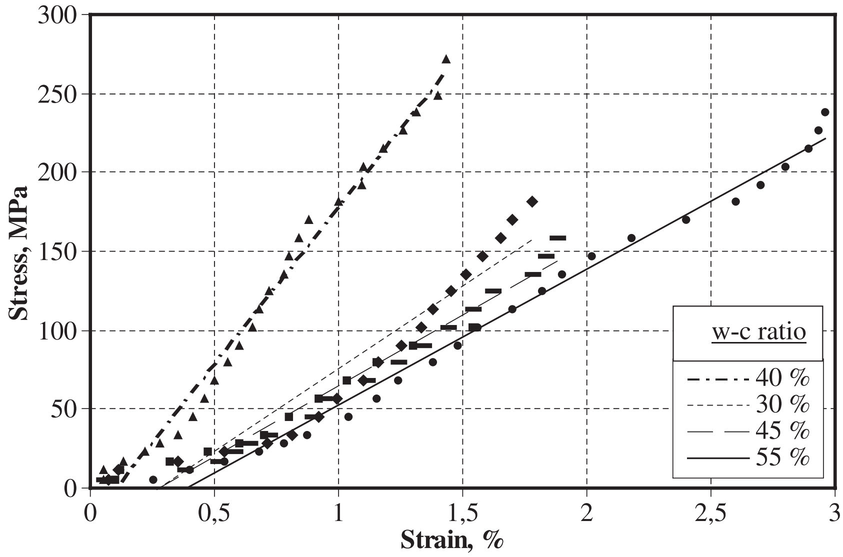

Fig. 7. Stress–strain relationship of concrete with PC 42.5.

to 3359-kg/m^3 unit weight of heavyweight concrete is accepted to be sufficient in all studies. To achieve this, a unit weight of concrete is found between 3266 and 3279 kg/m^3. The reason for the unit weight being higher in Gürsoy's study [15] (shown in Fig. 8) is thought to originate from the differences between the unit weights of barites used. If the unit weight of heavyweight concrete is increased, improvement in shielding properties is seen. However, the thickness of shield should be determined after first considering the activity of the radioactive environment. The first barite used in the study was from the Karadeniz deposit and the others are from the Konya deposit. The differences between the unit weights of the same w/c ratio come from different unit weights of barites used for different dosages. The difference between the saturated unit weights of concretes at the same dosages as the w/c ratios comes from the different unit weights of cement used. Differences between the unit weights of Gürsoy [15] and these study results comes from a 5–7% unit weight difference between the barite minerals used. Our mechanical experiments conducted on heavyweight concretes showed that concretes have quite a high strength at low w/c ratios and low strength at high w/c ratios. Care should be taken in the preparation of concretes for those structures using high amounts of concretes and the same attention should be paid even if the cost of workmanship is increased.

As seen in Fig. 9, the difference in strengths between concretes produced at a dosage of 350 kg/m^3 PC 32.5 and

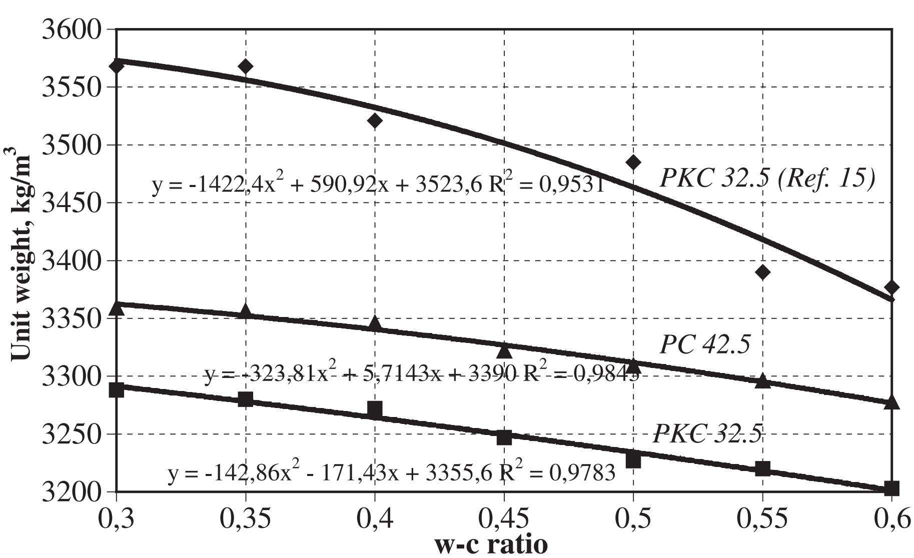

Fig. 8. Comparison of unit weights of different studies.

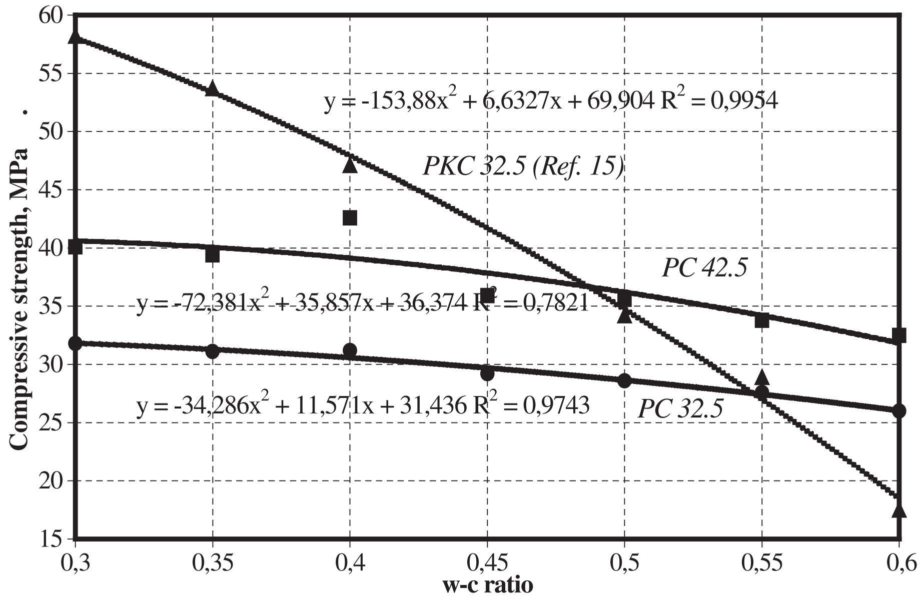

Fig. 9. Comparison of different study's compressive strength by w/c ratio.

42.5 is quite small. In previous studies, heavyweight concrete strengths between 62 and 76 MPa have been obtained [17]. Values of 50–55 MPa have been reached in studies performed in Turkey [15]. The priority in heavyweight concretes is to provide radioactive impermeability. For this reason, while choosing cement dosage for the first test, strength should be taken into consideration. This is due to heavyweight concretes having a wall function in most structures. Konya–Beyşehir–Höyük barites show physical and mechanical similarities with the barites used in previous studies. Unit weights are about 4000–5000 kg/m^3. The barite mineral that we use in heavyweight concrete production is found widely and abundantly in Turkey. In this case, the use of barite in heavyweight concrete production is thought to be economical. Although the cost of barite is three to four times more than that of normal aggregates, the necessary thickness of shield for heavyweight concretes will be much lower.

Generally, when referring to heavyweight concretes, it has been emphasized that it would be appropriate to choose the right w/c ratio for heavyweight concrete as between 0.30 and 0.50. In studies concerning heavyweight concretes, it is proposed that exceeding 0.50 w/c ratios is very unwise. Heavyweight concrete gives the maximum strength w/c ratio of 0.40 (Fig. 3). Moreover, when considering workability, despite the increased workability gained when using a ratio of 0.50, it has been seen to be more advantageous to use a ratio of 0.30 w/c when comparison for shrinkage risk at high cement dosages is considered. The w/c ratio of 0.40 by using an admixture that increases workability can be improved with regard to better workability. The concretes we used were prepared without using a plasticizer. As far as heavyweight concretes are concerned, plasticizer was used in heavyweight concretes at different w/c ratios produced by PKC 32.5. Therefore, the highest strength was obtained at w/c ratio of 0.30.

5. Conclusions

With PC 42.5, C 40 concrete at w/c ratios of 0.30 and 0.40, C 35 at w/c ratios of 0.35, 0.45, 0.50, and C 30 at w/c ratios of 0.55 and 0.60 have been produced. With PKC 32.5, C 30 concrete at w/c ratios of 0.30, 0.35, and 0.40 and C 25 concrete at w/c ratios of 0.45, 0.50, 0.55, and 0.60 have been produced. For shields requiring a quality of at least C 40, in obtaining the quality of C 40 and higher strengths, it is advantageous to use PC 42.5 cement. Using PKC 32.5 cement at C 20 and C 25 as low-strength heavyweight concrete, production will lower the cost and provide us the desired strength. Concretes at w/c ratio of 0.40 give the highest strength. The amount of void is related to water content. Voids can also be decreased with an increase in cement dosage; an increase in hydration heat released can be observed. Shrinkage should be prevented at low w/c ratios. However, using low hydration heat cements is helpful when a cement dosage of higher than 350 kg/m^3 is needed in heavyweight concrete production.

Because of the weight of the aggregates in heavyweight concretes, there is a risk of segregation. In order to prevent this, the mixing duration should be as low as possible and finer aggregates should be used. In Turkey's conditions, barites used as heavyweight concrete aggregates are found widely and easily. For this reason, in Turkish nuclear reactors and hospitals where radioactive impermeability is required, the priority should be given to heavyweight concretes. It is believed that more worthwhile results will be reached by examining the structural properties of concrete and the performance of radioactivity in the same study.

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