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Full Length Research Paper

An investigation on the concrete properties containing colemanite

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A radiation dose above the maximum permissible limit is harmful to our environment and our bodies. Study of radiation absorption in material has become an important subject to protect living creature and environment from harmful effect of radiation. Thus it is desirable to have the knowledge about the effective materials for neutron and gamma ray shielding. Concrete is the most widely used construction material in the world for this purpose. The aggregate of concrete plays an essential role in modifying concrete properties and physical-mechanical properties of concrete affect significantly shielding properties of concrete. This paper summarizes the results of investigation carried out on the concrete containing colemanite at different ratios. The intent of this research was to investigate the effect of the colemanite on physical and mechanical properties of concrete using colemanite as replacement aggregate. Slump, air content, compressive strength, split tensile strength, Schmidt hardness, modulus of elasticity, freeze-thaw durability, unit weight and pulse velocity were physical and mechanical properties investigated. It was observed that increasing colemanite ratio in volume has affected engineering properties of concrete and colemanite replacement up to 30% can be considered acceptable.

Key words: Colemanite, concrete, mechanical properties, concrete radiation shielding.

INTRODUCTION

As the human population and industrial demands grow, nuclear technology has oriented humanity towards using synthetic energy to complement conventional energy sources, which are running out. Constructions of nuclear power plants have been increased for many purposes, especially for energy supply all around the world. However, the issue of the potential impact of nuclear leakage on the environment, and a potential crisis is attracting much interest and stimulating many discussions (Kan et al., 2004). Living isolated from radiation is almost impossible in the modern world. Human and animal are subjected to natural or artificial radiation in the environment due to increase living standard. Also medical facilities like radiotherapy room need a well-shielded room. Thus, to protect living creature has been first aim.

Although lead has been used for shielding structures such as nuclear power plant, there is a wrong concept on it. For some cases, for instant, lead has been insufficient to shield neutrons. For this purpose, concrete is considered as an excellent and versatile shielding material widely used for shielding in nuclear power plants, particle accelerators, research reactors, laboratory hot cells and medical facilities. It is a relatively inexpensive material, which may be easily handled and cast into complex shapes. It contains a mixture of many light and heavy elements and therefore has good nuclear properties for the attenuation of photons and neutrons. Shielding characteristics of concrete may be adapted wide range of usage (Kaplan, 1989; El-Sayed et al., 2002).

In all nuclear installations, concrete is the most commonly used shielding material to protect from neutron radiation. It is a common practice to add boron to concrete in order to try enhance the thermal neutron

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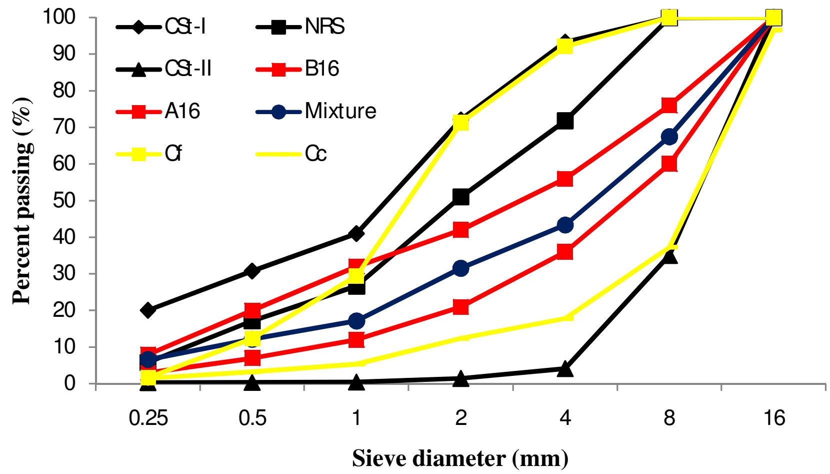

Figure 1. Grading curves of aggregates and mixture.

attenuation properties and to suppress secondary gamma-ray generation. Since pure boron is difficult to obtain by common extraction methods, the use of boron-bearing minerals is more economical and practical (Yarar and Bayülgen, 1994). Boron is one of the most important underground richness of Turkey, having about 60% of the world boron reserves. Commercial boron ores of Turkey are colemanite, tincal and ulexite (Demir and Keleş, 2006). Colemanite ($2CaO.3B_2O_3.5H_2O$) is a calcium borate mineral with hardness between 4 and 4.5 and specific gravity of about 2.4 g/cm^3. Pure colemanite has a B_2O_3 content of about 51%. Although colemanite has been fairly widely used in radiation shielding concrete, there is another point to consider that concrete used in nuclear applications must have adequate and satisfactory structural and engineering properties such as like compressive strength, shrinkage, workability, tensile strength and modulus of elasticity, which is a factor of importance in large stationary installations (Kaplan, 1989).

Ordinary concrete is made with Portland cement, ordinary aggregates of normal weight and water. Many materials have been added to concrete to improve many of its properties. Aggregates, which are the largest constituent (about 70 - 80% of the total weight of normal concrete), play an essential role modifying engineering properties of concretes (Khatita et al., 2009) and the type and quantity of aggregate in the concrete, are important components for radiation protection properties of concretes (Akkurt et al., 2006).

Several studies as follows were conducted on radiation shielding properties of materials containing boron and colemanite. Icelli et al. (2003) investigated X-ray transmission factors of some boron compounds. Shiao and Tsai (1989) have made a study on improving masonry cement for the solidification of borate wastes and found out that boron compound decrease radiation transmission of concrete. Okuno (2005) investigated neutron shielding material based on colemanite and epoxy resin. And Yarar (1996) studied activation characteristics of concrete shields containing colemanite. However, very little information has been conducted about engineering properties of concrete containing boron or colemanite. In the study of Gencel et al. (in press), rats were housed in concrete-protected cages and then irradiated to investigate protective effect of radiation shielding concrete produced with colemanite. In the present work, we aimed to investigate effects of colemanite used as aggregate at different volumes on concrete properties in point of fresh and hardened engineering properties.

MATERIALS AND METHODS

Properties of concrete-making materials are presented in this section. And the experimental studies of concretes produced with colemanite were described. Information about physical and mechanical experiments on concrete with colemanite is also provided.

Aggregates

Aggregates typically constitute 70 - 80 wt. % of concrete, aggregate types and sizes play an essential role in modifying concrete properties. We have created plain concrete (PC) using limestone-based aggregates with three different grain sizes: up to 3 mm size crushed stone (CSt-I), up to 7 mm size natural river stone (NRS) and 7 - 15 mm size crushed stone II (CSt-II). The aggregates were obtained from Atabey, Isparta, Turkey, graded, washed and cleaned of clay and silts. To reduce difficulties of producing, mixing and placing of concretes and to prevent segregation of aggregates in the fresh concretes, the maximum aggregate size was selected as 16 mm diameter. Results of sieve analysis of fine and coarse aggregates used are presented in Figure 1.

Colemanite was obtained from ETI Mine Works Inc., Turkey and prepared as aggregate by sorting it via sieves into two groups as course (C_c) and fine (C_f). Physical property of all aggregates was listed in Table 1. Chemical composition of colemanite was listed in Table 2.

Table 1. Physical and mechanical properties of aggregates.

Aggregate codes	Specific gravity (g/cm^3)	Water absorption (%)	Loose unit weight (kg/m^3)
CSt-I	2.61	2.91	1913
NRS	2.63	3.13	1830
CSt-II	2.70	0.83	1676
C_f	2.41	3.28	1455
C_c	2.42	1.35	1315

Table 2. Chemical composition of colemanite (weight %).

	C_c	C_f
B_2O_3	41.24	39.48
CaO	24.35	24.42
MgO	1.42	1.59
Fe_2O_3	0.44	0.76
SiO_2	5.07	6.38
LOI*	24.28	24.83

* Loss of ignition.

Table 3. Chemical composition of cement (weight %).

Total SiO_2	22.90
Al_2O_3	5.32
Fe_2O_3	3.63
CaO	55.83
MgO	1.99
SO_3	2.62
Cl	0.00
LOI*	4.20
Free CaO	0.82
Total Admixture	19.45

* Loss of ignition

Cement

The Portland cement used in all mixtures was produced according to the European Standards EN-197/1 and labeled as CEM II/A-M (P-LL) 42.5N in this study. The cement was manufactured at Goltas cement factory in Isparta, Turkey. Physical and mechanical properties and chemical analysis of cement are presented respectively in Tables 3 and 4. We note more than doubling of the compressive strength between 2 and 28 days and nearly doubling the flexural strength in the same period.

The Le Chatelier method of cement characterization is based on using a 30 mm longitudinally split cylindrical mold with 2 indicators containing the cement paste - exposed to boiling water at the atmospheric pressure for 3 h. The cement is acceptable if the distance between the indicators is ≤ 10 mm (European Committee on Standardization).

The Blaine method follows the ASTM C-204-07 standard. The Blaine air permeability apparatus allows drawing a definite quantity of air through a prepared bed of cement of definite porosity. The permeability cell is a rigid cylinder made of stainless steel.

Mix proportions

To investigate the effect of colemanite on the physical and mechanical properties of concrete, the mixture of concrete containing colemanite in different volumes and plain concrete were designed. Concrete for radiation shielding can be proportioned using the ACI method of absolute volumes developed for normal concrete (Mindess and Young, 1981). The use of this method is generally accepted and is considered to be more convenient for radiation shielding concrete (Postacioglu, 1955). Hence, the absolute volume method was used for the calculation of the concrete mixture. Mix proportions and volumes of aggregates in the mixture are listed in Tables 5 and 6, respectively.

In this study, many trial tests were conducted to determine the water/cement ratio (w/c). Basing on results of these tests and considering workability without using chemical (plasticizer) and mineral admixtures, optimum w/c was observed as 0.42. It is well known that w/c should be kept below 0.50 to prevent cracking. Besides, the ACI Manuel of Concrete Practice advices that neither type III cement nor accelerators should be used to avoid high and rapid hydration heat and potential consequent cracking (ACI, 1996) and for radiation shielding concrete, cement content is generally quite high, greater than 350 kg/m^3. This helps to improve the shielding characteristics of the concrete because of the high bound water content of the paste (Mindess and Young, 1981; Topcu, 2003). Special performance requirements using conventional materials can be achieved only by adopting low w/c, which requires high content of cement (Bharatkumar et al., 2001). Thus, cement content and w/c was 400 kg/m^3 and 0.42 in the all mixtures respectively. 10% (CC10), 20% (CC20), 30% (CC30), 40% (CC40) and 50% (CC50) of colemanite aggregate in volume in the testing program to examine the effect of colemanite on the physical and mechanical properties of concrete were replaced with lime stone based aggregates. Since segregation affecting both shielding and engineering properties of concrete can be more pronounced in producing concrete, the concrete should be handled, transported, placed, compacted and finished carefully in every step in point of keeping homogeneity of fresh concrete. The plain concrete (PC) would be used for comparison purpose.

Mixing, curing and testing specimens

In a typical mixing procedure, the materials were placed in the mixer with capacity of 56 dm^3 in the following sequence: first course aggregates, fine aggregates followed by cement, initially dry material mixed for 1 min and finally addition of 80% of water. After 1.5 min of mixing, rest of the mixing water was added. Total mixing time was 5 min. It was observed that flocculation occurred and course aggregates were crashed during the mixing process. All the concrete specimens were cast in molds and the molds of specimen were subjected to vibration. Demoulding time was observed as over 48 h. and then the specimens were cured in lime saturated water at

Table 4. Physical and mechanical properties of Portland cement.

Compressive strength (MPa)			Flexural strength (MPa)			Initial setting time (hour)	Final setting time (h)	Le Chatelier (mm)	Specific gravity (g/cm^3)	Blaine (cm^2/g)
2 Days	7 Days	28 Days	2 Days	7 Days	28 Days					
22.5	36.6	47.8	3.7	5.6	6.9	2.25	3.15	1	3.15	4150

Table 5. Mixtures of heavyweight concrete composition for 1 m^3.

	PC	CC10	CC20	CC30	CC40	CC50
Cement (kg)	400	400	400	400	400	400
Water (kg)	168	168	168	168	168	168
W/C	0.42	0.42	0.42	0.42	0.42	0.42
Air content (%)	1.5	1.5	1.5	1.5	1.5	1.5
CSt-I (kg)	447.30	402.57	357.84	313.11	268.38	223.65
NRS (kg)	443.44	399.10	354.75	310.41	266.06	221.72
CSt-II (kg)	926.83	834.14	741.46	648.78	556.10	463.41
C_f (kg)	-	79.40	158.80	238.19	317.59	396.99
C_c (kg)	-	82.43	164.86	247.28	329.71	412.14

Table 6. Volumes of aggregates in the mixture (%).

Code	CSt-I	NRS	CSt-II	C_f	C_c
PC	25.0	25.0	50.0	-	-
CC10	22.5	22.5	45.0	5.0	5.0
CC20	20.0	20.0	40.0	10.0	10.0
CC30	17.5	17.5	35.0	15.0	15.0
CC40	15.0	15.0	30.0	20.0	20.0
CC50	12.5	12.5	25.0	25.0	25.0

20 ± 2°C temperature prior to testing.

Slump (ASTM C 143) and air content (ASTM C 231) of the fresh concrete were also measured for each mix, providing useful data to determine the amount of voids. Three items of specimens made from the above six mixtures were fabricated. The 15 × 15 × 15 cm cubic specimens were primarily used for compressive strength, Schmidt test and pulse velocity of concrete. Cylinders of 150 mm in diameter and 300 mm in height were used to determine the properties of concrete, including the modulus of elasticity, stress-strain and splitting tensile strength.

RESULTS and DISCUSSION

Physical properties of concrete

Fresh concrete is a transient material with continuously changing properties. It is, however, essential that hardened properties of concrete have been affected by fresh phase of concrete. As well as to form a homogenous batch, usually void-free concrete, testing and measuring this fresh solid mass has been crucial. A wide range of techniques and systems are available for these processes. Slump test has been widely accepted and used for this purpose (Newman and Choo, 2003). Figure 2 shows that slump values of mixes were decreased by dependant on increase colemanite ratio in concrete. And it was observed that fresh concrete has flocculated more at increase of colemanite ratio in volume during the mixing process. The reason for slump loss may be this flocculation. Cement paste reacts with colemanite aggregates resulting in melting, which may cause the flocculation (Figure 3). However, ACI and ASTM defines workability as property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated and finished (ACI, 1990). Besides, that property determines the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity (ASTM, 1993) and slump of 50 mm is considered enough to fulfill

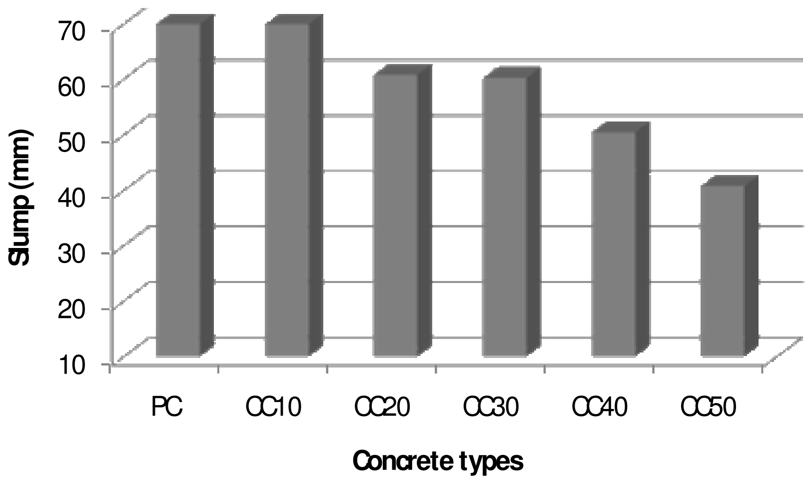

Figure 2. Slums values of concretes.

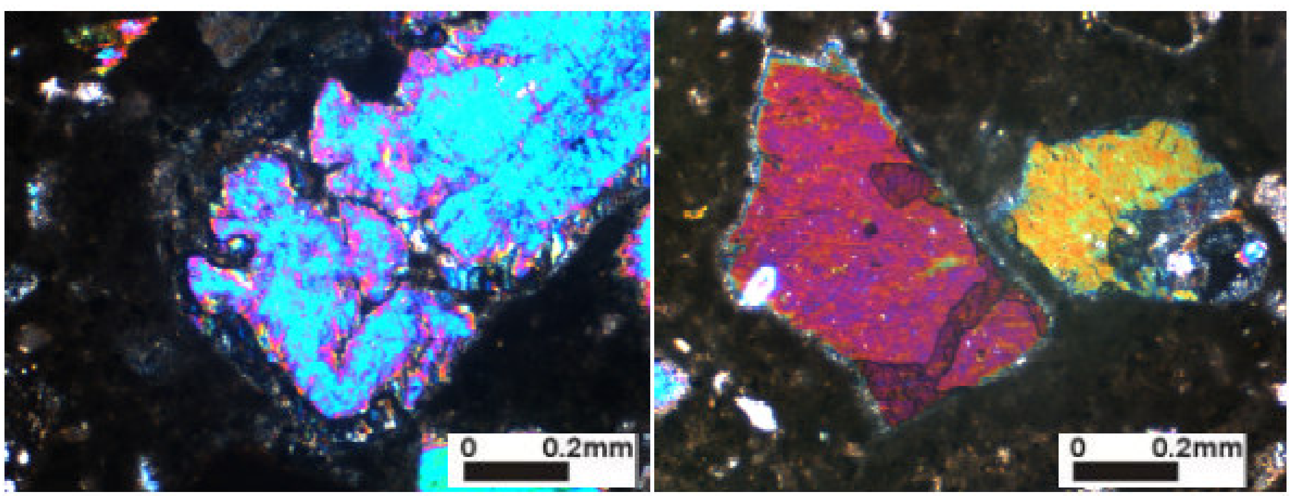

Figure 3. Polarization view of interaction zone between cement paste colemanite aggregate.

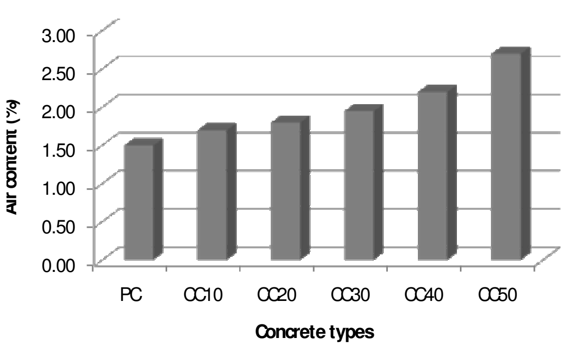

Figure 4. Air content.

these definitions. In presented mixture design, colemanite content up to 30% can be added to concrete when the workability is considered.

Air content is another test method to have opinion about the homogeneity of fresh concrete. Based on test result, as seen in Figure 4, air content was observed that concretes containing colemanite up to 30% have 1.5% aimed air content. Flocculation occurs over 30% colemanite content in concrete.

According to studies conducted by (Boncukoglu et al., 2002; Erdogan et al., 1998; Olgun et al., 2007), the cement produced with boron has affected the setting time of concrete. Also it is well-known that boron in cement has caused high hydration heat induced cracks. In this

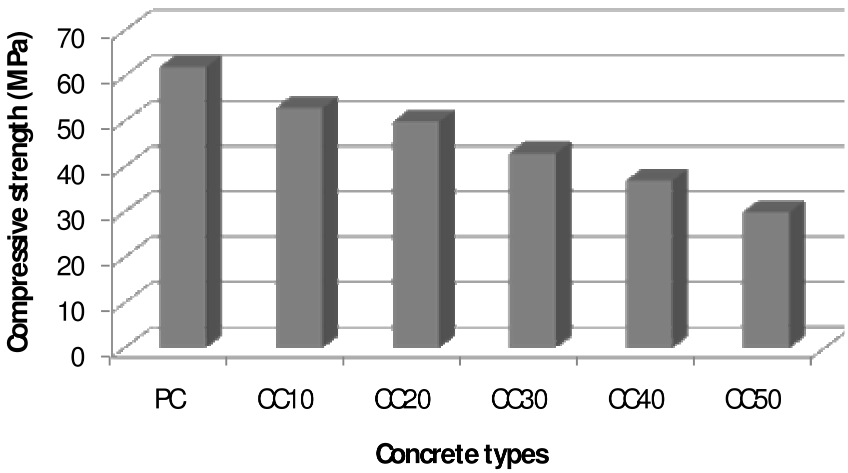

Figure 5. Compressive strengths of concretes.

study, colemanite including boron was used as aggregate in concrete and it was observed that even if colemanite was used as aggregate, it could delay the setting concrete. The reason behind that may be fine colemanite ratio to which course crumbled colemanite attributed since water soluble boron minerals, even in small quantities, delay the setting of concrete. Stable and insoluble boron minerals are generally not available in large quantities for concrete aggregate. The effects of colemanite on the setting of Portland cement concrete also depends upon the possible presence of sodium borate impurities and on the temperature, as well as on the chemical composition of the ore which can vary from batch to batch (Kaplan, 1989). Also, increasing fine particles due to aggregates crumbled in the mixtures may cause flocculation.

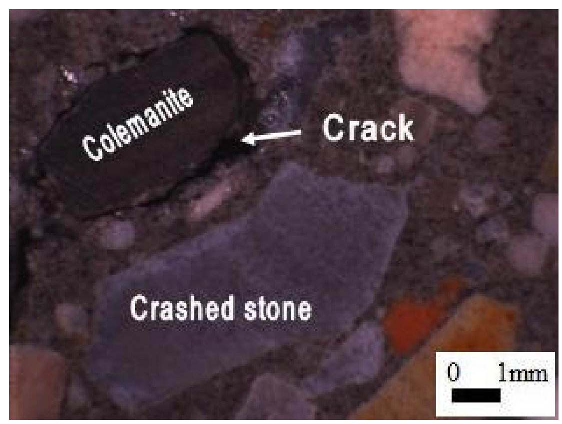

Figure 6. Interface of colemanite and lime-based aggregate with matrix.

Mechanical properties of concrete

The procedures for testing most fundamental mechanical properties, such as compressive strength (ASTM C 39-86), splitting tensile strength (ASTM C 496-87), modulus of elasticity (ASTM C 569-87), freeze-thaw durability (ASTM C 666) and pulse velocity (ASTM C 597-02) were tested. The pulse velocity and freeze-thaw durability were measured on 15 cm cubic samples.

Compression strength

It can be seen from Figure 5 that the 28-day compressive strength of concrete produced with colemanite was 14.51, 19.35, 30.65, 40.32 and 51.61% lower than that of PC, respectively. All concrete specimens with colemanite; showed decreasing strength with increasing colemanite ratio at volume. As seen from Figure 5, the colemanite ratio is inversely proportional to the compressive strength of concrete. This may be due to the interaction between cement paste and colemanite which causes weak adhesion between paste and aggregates (Figure 3) and structure of colemanite aggregate. We can see from Figure 6 that as a result of this interaction, wide and deep cracks occur around colemanite aggregate in the matrix compared to limestone-based aggregate. Reductions in compressive strength due to colemanite were parallel to the reduction of densities. Yarar and Bayulken (1994) reported that using different colemanite volumes at 0.50 w/c ratio could produce concrete strength between 8 and 22 MPa. Even though 20 MPa seems adequate, in fact more is needed in regard to prolong life and durability and seismic-resistant structures.

Splitting tensile strength

The splitting tensile test was used to determine the tensile strength of concrete samples with colemanite at

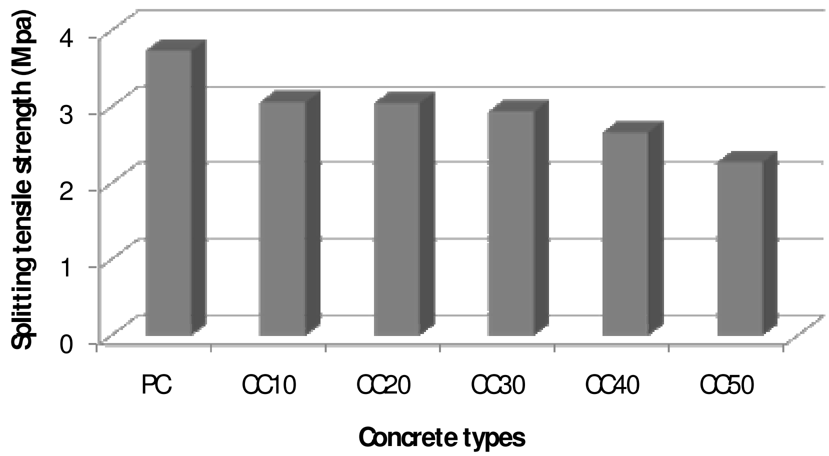

Figure 7. Relationship between colemanite ratio and 28 day splitting tensile strength.

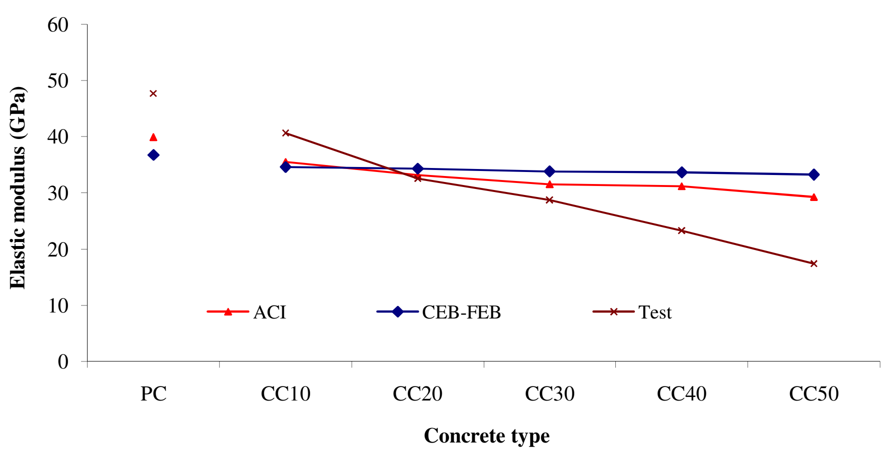

Figure 8. Elastic modulus variations of concrete.

different ratios. As seen from Figure 7, the splitting tensile strength of concrete with colemanite was lower than that of PC. Splitting tensile strength values ranged from 3.7 to 2.2 MPa. The maximum splitting tensile strength, 3.7 MPa was obtained from PC. The lowest 28-day splitting tensile strength, 2.2 MPa was found for the CC50. It also decreases with increasing colemanite ratio. It seems that this was due to effect of increasing air voids in the mixtures. It varied between 8 and 10% of 28 day compressive strength (Neville, 1996).

Modulus of elasticity

The modulus of elasticity (E) of all concrete measured in this study were obtained at an age of 28 days. The curing condition of specimen was the same as the condition for determining compressive strength. To take data, a frame named strain-gauge having sensitivity of 0.002 on measurement placed to cylindrical specimens was used.

The E modulus was obtained from σ-ε curves using Secant Method. And the test results were compared with E modulus predicted from the ACI and CEB-FIP codes and dynamic modulus. As it can be seen from Figure 8, concretes with colemanite had low modules of elasticity and it showed decreasing with increasing colemanite in the mixes. Modules of E on experimental test have varied between 18 and 40 GPa depending on colemanite content.

Pulse velocity test

Figure 9 shows, pulse velocity values ranged from 2691 to 4073 m/s. The PC had the highest value and the pulse velocity of concrete with colemanite has decreased with on colemanite ratio in concrete. The reason for this is formation of air voids increased by increasing colemanite

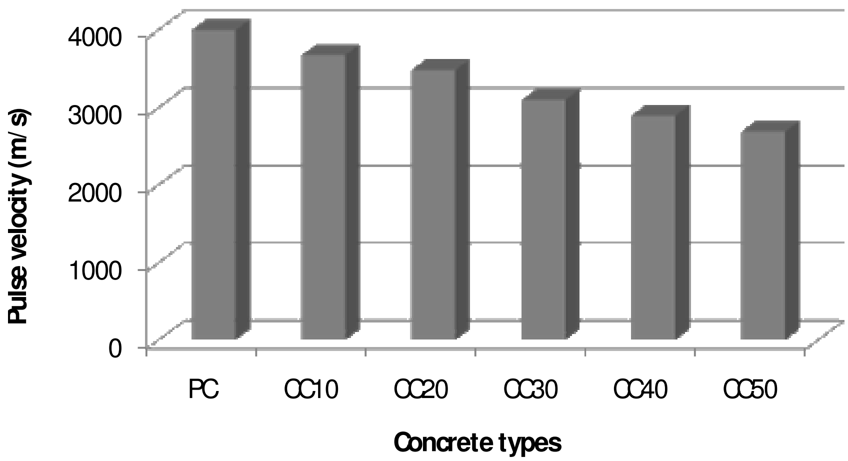

Figure 9. Pulse velocity of concretes.

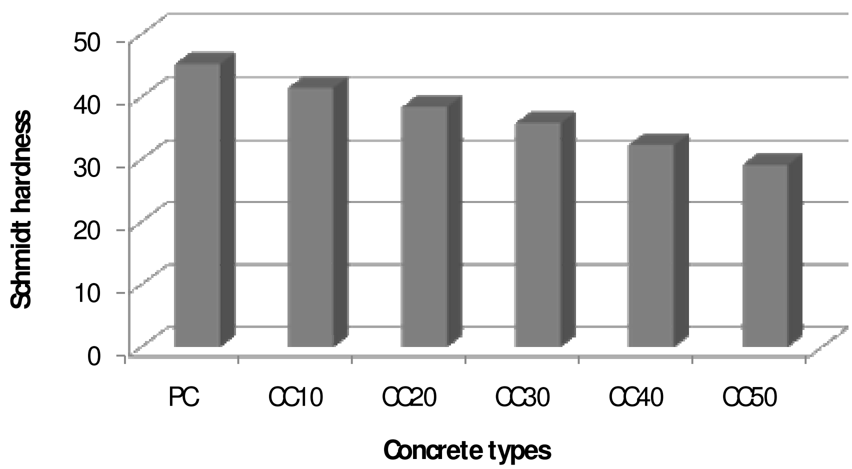

Figure 10. Schmidt harness of concretes.

in the concrete. Nonetheless, Whitehurst (1951) classified the concretes as excellent, good, doubtful, poor and very poor for pulse velocity values of 4500 m/s and above, 3500 - 4500, 3000 - 3500, 2000 - 3000, and 2000 m/s, respectively. According to this classification, more than 30% of colemanite in the concrete is not adequate in this respect to strength.

Schmidt hardness test

In order to obtain information on the hardness of concrete, the Schmidt hardness experiment was applied to concrete samples. This test, one of the most popular nondestructive testing methods, is an economic and easy method to evaluate the compressive strength of concrete. A uniform compressive stress of 2.5 MPa was provided to the test specimen along the vertical direction, the same direction of casting direction, before striking it with the hammer to prevent the dissipation of hammer striking energy due to the lateral movement of the specimen. Striking points were uniformly distributed to reduce the influence of local aggregates distribution, and the rebound number of the specimen was obtained by averaging the results. Rebound values on Schmidt hammer readings were found to decrease with increasing colemanite content when compared with the PC (Figure 10).

Unit weight

Linear attenuation coefficient is the probability of a photon interacting in a particular way with a given material, per unit path length, and is of great importance in radiation shielding. However, linear attenuation coefficients depend on the density of shielding materials (Kaplan, 1989; El-Sayed et al., 2002).

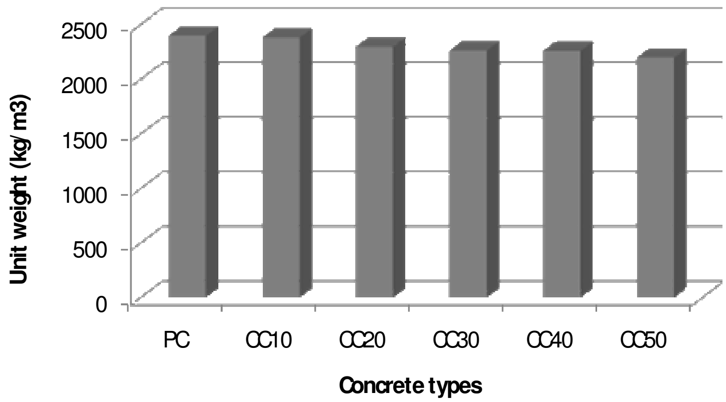

Figure 11. Unit weight of concretes.

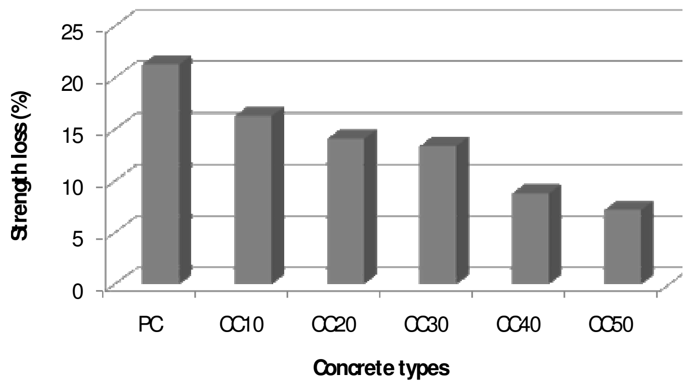

Figure 12. Freeze-thaw durability of concretes.

So unit weight of concrete is one of the most desired properties of it for especially gamma rays and x-rays shielding. The shielding effectiveness of concrete is to a large extent dependent on its density. If unit weight of concrete is increased, improvement of shielding properties is seen. The greater the density, the smaller the thickness of concrete required. Due to density of colemanite, increasing of colemanite ratio in volume makes the unit weight of concretes decrease as seen from Figure 11. Also because of flocculation of fresh concrete with colemanite, samples have not gained full compaction in the casting process affecting density.

Freeze-Thaw durability

Micro-cracks mainly exist at cement paste-aggregate interfaces within concrete even prior to any load and environmental effects. When the number of Freeze-Thaw Cycle (FTC) increases, the degree of saturation in pore structures increases by sucking in water near the concrete surface during the thawing process at temperatures above 0°C. Some of the pore structures are filled completely with water. Below the freezing point of related pores, the volume increase of ice causes tension in the surrounding concrete. If the tensile stress exceeds the tensile strength of concrete, micro-cracks occur. By continuing FTCs, more water can penetrate the existing cracks during thawing, causing higher expansion and more cracks during freezing. The load carrying area will decrease with the initiation and growth of every new crack. So the compressive strength will decrease with FTCs (Shang et al., 2008). In this work, all specimens were subjected to 30 FTCs, 2 h freezing and 1 h thawing.

Figure 12 shows that all concrete types had lost strength, however series of colemanite had less strength lost than that of PC. Compressive strength loss of concrete was following: PC 21.3%, CC10 16.3%, CC20 14.1%, CC30 13.4%, CC40 8.8% and CC50 7.2%. The value of strength loss of concrete with colemanite, increasing in volume, observed here somewhat less than that of PC. This is inversely proportional to the air content of colemanite concretes. More air voids in concrete leads to high water absorption. PC had the highest compressive strength loss with 21%, nonetheless, it is acceptable level according to ASTM C 666 code. Also it was observed that there was no reduction of the weight of the specimens and desquamation of concrete surfaces after FTCs.

Conclusion

Using colemanite ranging from 10 up to 50% as aggregate in concrete has a negative effect, in respect to both physical and mechanical properties. When increased (over 50%), this effect would be more.

It has delayed the setting time of concrete. It is recommended that an addition up to 30% of colemanite into concrete is considered as the acceptable level in the workability and strength of these concretes. More investigation to solve problems about physical and mechanical properties of concrete containing colemanite should be done.

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