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Effect of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete

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ABSTRACT

The main objective of this study is to provide more data on the effects of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete. In the experimental program, mixtures were prepared by partially replacing natural aggregate by expanded perlite and as a result, unit weights of lightweight concretes in fresh state varied between 700 and 2000 kg/m^3. Water to cement ratio was kept constant in all mixtures. Compressive strength, modulus of elasticity, water absorption and capillarity coefficient of the mixtures were determined. Thermal conductivity of the specimens was also obtained. Test results show that the compressive strength and modulus of elasticity decreases with increasing in perlite content. Water absorption and sorptivity coefficient, however, increase with the higher perlite contents. The test results indicate that the thermal conductivity is substantially improved with the use of perlite and a strong relationship between thermal conductivity and unit weight is obtained.

1. Introduction

Perlite is a siliceous volcanic glass, the volume of which can expand substantially under the effect of heat. When heated above 870 °C, its volume increases 4–20 times of the original volume [1]. As a result of this volume increase, and its porous structure, water absorption of the expanded perlite is significantly high. In addition, the density of expanded perlite is very low compared to that of normal perlite. Perlite is being used in different areas such as construction materials, agriculture, medical and chemical industry [2]. The absence of any apparent health hazard and fire resistance is also increasing its usage rate [3]. Compared to other materials such as exfoliated vermiculite, expanded clay or shale, pumice, mineral wool, competitive price of expanded perlite may be an important advantage. Turkey has one of the largest perlite deposits in the world. It is estimated that the total amount of perlite reserve in the country is approximately 4.5 billion tons [4]. The utilization of perlite in the country, however, is very limited and the majority of the perlite is used mostly in plaster and as filling materials. The annual perlite production in Turkey is around 150,000 tons. Although the current use of expanded perlite is very low, there is a growing demand from construction industry [4].

Concrete is a composite material and since approximately 75% of the concrete volume is occupied by aggregate, the properties of aggregate greatly affect performance of concrete. Several properties of aggregate, such as chemical and mineral composition, shape, roughness, specific gravity, hardness, strength, and pore structure depend on the properties of parent rock [5]. The use of lightweight and porous aggregates as a constituent of concrete enables production of lightweight concrete. Due to its low density, expanded perlite is a suitable material to produce lightweight concrete [6,7]. The high water absorption of expanded perlite can provide water for the hydration of cement at the later ages which is beneficial in concrete [8]. Such internal curing can be important especially for concretes with low water/cement ratios. Expanded perlite can also have pozzolanic activity and can be used as a mineral admixture when finely ground [9,10].

Economical and environmental constraints are bound to increase in the coming years and one of its effects on construction industry is to obtain more energy efficient buildings and construction materials [11]. An important way of achieving such buildings is to improve the thermal insulation properties. Reduction of the heat loss in buildings decreases the consumption of energy, thus, reduces the cost of heating and cooling [12]. As a result of the lower use of energy, improvements in thermal insulation also affect sustainability. Due to its higher porosity, lightweight concrete is a suitable material for thermal insulation of structures [13]. Properties of lightweight concrete, however, are usually different compared to those of normal concretes. The main objective of this study is to provide more data on the effects of expanded perlite aggregate on the mechanical properties and thermal conductivity of lightweight concrete. In the experimental program, the natural aggregate was partially replaced by the expanded perlite with increments of 20% up to 100%, details of which are given below.

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Table 1
Aggregate grading.

Aggregate type	Percentage passing				
	Sieve size (mm)				
	4	2	1	0.5	0.25
Expanded perlite	100	54	31	20	16
Natural sand	100	96	82	54	18

2. Experiments

2.1. Materials

In this study, an expanded perlite obtained from Bergama-Izmir, located in the west region of Turkey, was used. The perlite used consisted mainly of 73% SiO_2 and 16% Al_2O_3. Unit weight and water absorption of the perlite were 54 kg/m^3 and 310%, respectively. In the experimental study, locally available natural sand with a specific gravity of 2620 kg/m^3 was also used. Particle size distributions of the expanded perlite aggregate and natural sand are given in Table 1. As seen from the table, the expanded perlite is coarser between the sieves of 2 and 0.5 mm. Thus, as the expanded perlite content increases, the aggregate gradation in concrete is modified slightly for each replacement ratio. Same ordinary Portland cement (CEM I 42.5 R), superplasticizer and air entraining admixture was used in all the mixtures.

2.2. Mixtures

In the experimental study, 6 mixtures having different unit weights were prepared using expanded perlite and natural sand. The mixture proportions are shown in Table 2. Effective water/cement ratio was 0.55 and kept constant in all mixtures. The effective water occupies space outside the aggregate particles in the mixture and to be able to obtain the same effective water/cement ratio in all the mixtures, the expanded perlite was kept in water for 30 min so that the perlite can absorb water and do not affect the effective water/cement ratio. This pre-absorption water contents were calculated from the 30-min water absorption of the expanded perlite and included in Table 2.

The mixture proportioning was based on the absolute volume method. The unit weights of the concretes were reduced as a result of the replacement of the natural sand by the expanded perlite. The replacement was performed based on the equal volume basis and the replacement ratio was increased from 0% (normal concrete) to 100% with steps of 20%. To obtain approximately the same workability of 15 ± 2 cm slump, a superplasticizer was used in some of the mixtures. Air entraining admixture (0.3% of the cement weight) was used in all the mixtures to reduce the unit weight of the mixtures. The mixtures were designated as NC and EPC which denote the normal concrete and expanded perlite concrete, respectively. The numbers (20, 40, 60, 80 and 100) following EPC indicate the replacement percentage. All mixtures were prepared in a laboratory mixer with vertical rotation axis by forced mixing.

All specimens were kept in their molds for 24 h. After demolding, they were stored in a water tank, saturated with lime at 20 °C until the age of 28 days. At this age, the specimens were taken out of the curing tank and kept in laboratory conditions (50% RH at 20 °C) until testing days.

2.3. Test procedures

Standard tests were done in accordance with European Standards (EN 206 and EN 12390). Three 70 mm cubes were used for the standard compressive strengths of the concretes. Three cylinders 100 mm in diameter and 200 mm in height were prepared for the determination of modulus of elasticity and the elastic moduli were calculated from the stress–strain curve for stresses below approximately 30% of the ultimate strength. Sorptivity tests were performed on 70 mm × 70 mm × 280 mm prisms according to EN 13057. Water absorptions of the specimens by immersion were also obtained. Thermal conductivity coefficients of the specimens were determined according to EN 12667. All the tests were carried at the age of 35 days. Except the thermal conductivity tests, all the tests were performed on air dry specimens.

3. Results and discussion

3.1. Unit weight

As seen in Table 2, the unit weight of the fresh mixtures varied between 696 kg/m^3 and 2015 kg/m^3. The mechanical tests were carried out on air-dry specimens. However, since the moisture content during testing may affect the results obtained, the thermal diffusivity testing was made on oven-dried specimens. These unit weights during the tests are shown in Table 3. For a better illustration of the effect of expanded perlite on unit weights, the fresh densities of the mixtures are also included in this table. When the unit weights in the fresh state and in air dry condition are compared, it can be seen that for the mixture containing only natural

Table 2
Mix proportions of lightweight concretes.

Concrete codes	NC	EPC20	EPC40	EPC60	EPC80	EPC100
Cement (kg/m^3)	317	337	326	301	297	295
Water (kg/m^3)	175	185	179	166	163	162
Pre-absorption water (kg/m^3)	0	37	71	100	131	162
Effective water/cement ratio	0.55	0.55	0.55	0.55	0.55	0.55
Natural sand 0–4 mm (kg/m^3)	1517	1288	937	581	286	0
Expanded perlite 2–4 mm (kg/m^3)	0	17	33	47	61	76
Superplasticizer (kg/m^3)	4.8	5.1	1.5	0	0	0
Air entraining admixture (kg/m^3)	1.0	1.0	1.0	0.9	0.9	0.9
Fresh unit weight (kg/m^3)	2015	1870	1549	1196	939	696

Table 3
Unit weights of the specimens during the tests.

Concrete codes	NC	EPC20	EPC40	EPC60	EPC80	EPC100
Unit weight at the fresh state (kg/m^3)	2015	1870	1549	1196	939	696
Unit weight during mechanical tests (kg/m^3)	1937	1775	1402	980	673	392
Unit weight during thermal diffusivity testing (kg/m^3)	1833	1677	1316	909	613	354

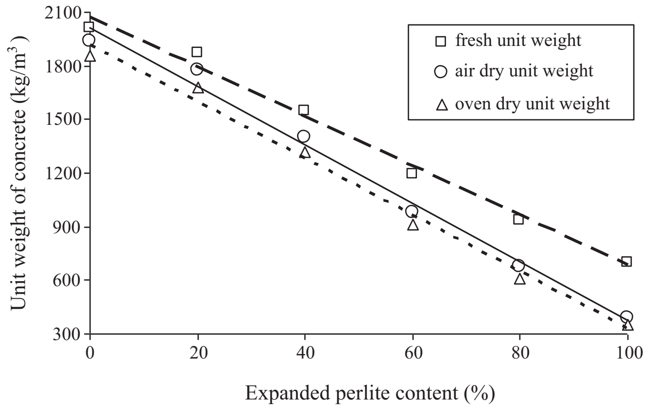

Fig. 1. Effect of expanded perlite aggregate on the unit weight of concrete.

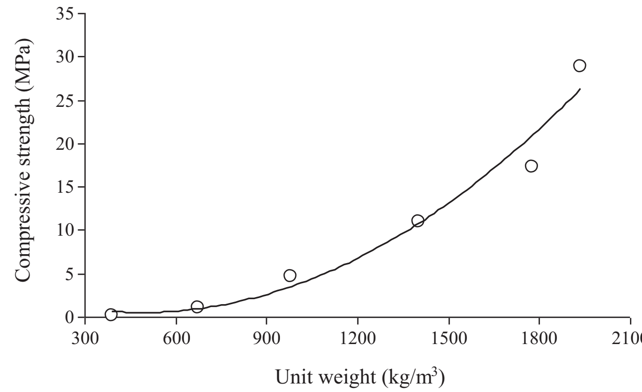

Fig. 2. Effect of expanded perlite aggregate on the compressive strength.

aggregate (NC); the air dry unit weight is only 4% less than the unit weight at the fresh state. This reduction in unit weight is 9% for the mixture containing 40% perlite (EPC40). For higher perlite contents, however, the ratio of the air dry unit weight to the fresh unit weight is reduced substantially and these reductions are 28% and 44% for the mixtures produced with 80% and 100% perlite, respectively. The substantial reduction of the unit weights due to air drying is an indication of the presence of larger and higher amounts of open pores to the surface. Compared to those of the air-dry unit weights, the ratios of the oven dry unit weights to the fresh densities are even lower as expected. However, the difference between the air dry and oven dry unit weights are 10% at most. The changes in the unit weights are also shown in Fig. 1.

As shown in Table 3 and Fig. 1, the unit weight of concrete can be reduced substantially by replacing normal aggregate by expanded perlite aggregate. Such reductions in unit weight can have important benefits on the performance of structures. The weight reduction in a concrete structure decreases the stresses in the structural elements, and since the stresses generated due to seismic loads are also dependent on the weight of the structure, reduction of the structural weight is beneficial in terms of earthquake resistance. Forces acting on the foundations of the structure are also reduced [14]. Thus, with a lower total weight of the structure, the structural details of the elements can be optimized; lower amounts of reinforcing steel and reduced cross sections can be obtained, which is important also from an economical point of view. Lower overall cost of the structure can be obtained as a result of the reduced weights. Reduced formwork pressure due to lower unit weight of the concrete is also beneficial in terms of formwork cost.

3.2. Compressive strength

Fig. 2 shows the effect of unit weight on the compressive strength of concrete. The mechanical properties of the mixtures are also shown in Table 4. As seen in the figure, compressive strength is reduced substantially with the unit weight of concrete. The reference mixture (NC) produced only with the normal aggregate has a unit weight of 1937 kg/m^3 and its cube compressive strength is 28.8 MPa. The unit weight of the mixture in which 20% of the normal aggregate was replaced by the expanded perlite (EPC20), is 1775 kg/m^3 which corresponds to 8% reduction in the unit weight compared to the normal mixture. However, the compressive strength of the mixture containing 20% expanded perlite is 17.3 MPa, which is approximately 40% lower than that of the reference mixture. Substantial reductions in the compressive strength were obtained also for the higher expanded perlite contents. When the relationship shown in Fig. 2 is studied in more detail, it seems that there are two distinct slopes in this figure, thus, the relationship between the compressive strength and unit weight can be divided into two parts; one part is between a unit weight of about 1000 kg/m^3 and higher, and the other for the mixtures having unit weights less than 1000 kg/m^3 (Fig. 2). Because the slope of the curve is steeper for the unit weights more than 1000 kg/m^3, it may be concluded that when the natural aggregate is replaced by the expanded perlite, compressive strength is more affected in replacement ratios up to 40% (Fig. 2). Beyond this replacement ratio, although the strength continues to decrease, the rate of strength reduction is lower.

Lightweight concretes can be classified into different groups based on their unit weights and compressive strengths [15]. The mixture produced using 20% perlite has a compressive strength of 17.3 MPa and can be classified as a lightweight structural concrete. However, due to the lower compressive strengths, mixtures containing more than 20% expanded perlite can be classified as insulation concretes. It should be mentioned that all the mixtures produced in this study have the same water/cement ratio of 0.55 and it is possible to obtain higher strengths by reducing the water/cement ratio. On microstructural scale, concrete can be considered as a three-phase composite model consisting of mortar matrix (or cement paste), aggregate, and interfacial zone between cement paste and aggregate [16]. Properties of these constituents affect the properties of concrete, thus, as the normal aggregate is replaced by the porous expanded perlite, compressive strength of concrete is reduced due to lower strength of the perlite [17,18]. The air entrainment also contributed to the low strength of the concretes.

It should be mentioned that during the production of mixtures, if the expanded perlite aggregates were used in a dry condition,

Table 4
Mechanical and physical properties of the mixtures.

Concrete codes	NC	EPC20	EPC40	EPC60	EPC80	EPC100
Compressive strength (MPa)	28.8	17.3	10.9	4.6	1.1	0.1
Modulus of elasticity (GPa)	19.5	12.8	9.4	3.3	–	–
Thermal conductivity (W/mK)	0.6	0.57	0.53	0.35	0.21	0.13
Water absorption (%)	6.4	9.8	13.3	19.8	33.9	79.3
Sorptivity coefficient ($\times10^{-3}$ cm/s$^{1/2}$)	0.12	0.18	0.19	0.22	0.25	0.41

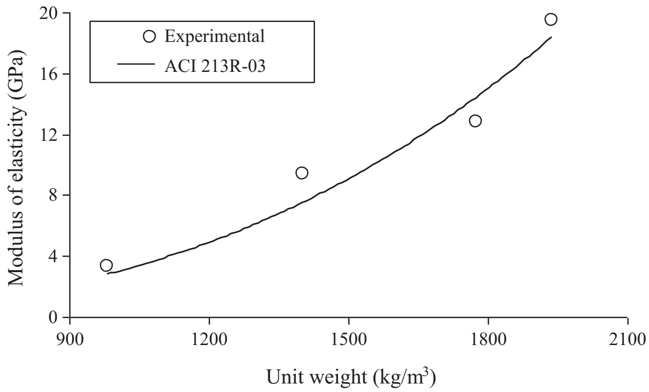

Fig. 3. Effect of expanded perlite aggregate on the modulus of elasticity.

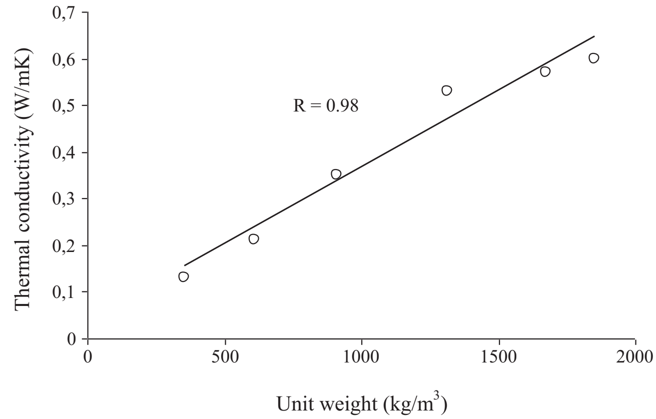

Fig. 4. Effect of expanded perlite aggregate on the thermal conductivity of concrete.

higher compressive strengths might have been obtained due to the fact that the aggregates absorbs the water in the mixture, thus effective water/cement ratio is reduced [19]. Such a mixture proportioning, however, can affect the workability of the concrete substantially. In this study, the expanded perlite aggregate was presoaked for 30 min to obtain the same effective water/cement ratio in all the mixtures.

3.3. Modulus of elasticity

The relationship between the unit weight of concrete and modulus of elasticity is presented in Fig. 3 and Table 4. As seen in the figure, when the unit weight of concrete is reduced due to the use of expanded perlite, lower values of modulus of elasticity were obtained. For example, mixture produced only with the natural aggregate has an unit weight of 1937 kg/m^3 and that of the mixture containing 40% expanded perlite is 1402 kg/m^3 (Table 3) and the reduction of unit weight is 28%. However, the modulus of elasticity of these mixtures is 19.5 and 9.4 GPa, respectively, which is a reduction of more than 50%. Modulus of elasticity of the mixture containing 60% perlite is only 3.3 GPa. The values for the 80% and 100% expanded perlite were not obtained.

The interface plays an important role on the stress–strain curve under uniaxial compression and is explained by progressive microcracking in the concrete. Microcracks start on the interfaces, and strain increases at a faster rate than the applied stress; thus, the stress–strain relation exhibits a typical curvature as the load increases and bond cracks penetrate into the matrix. An interconnected network of bond and matrix cracks then results in material discontinuity, and further load increase produces failure [20]. In the case of lightweight concrete, however, since the aggregates are much more porous and therefore have lower strength, the bond cracks can penetrate also into the lightweight aggregate. In addition, fresh cement paste can penetrate into the open pores of the expanded perlite aggregate, providing a good paste – aggregate bonding. The elastic matching of the aggregate and the hardened cement paste can also play a role in this behavior [21,22]. After testing, the examinations on the fractured planes indicate the cracks usually passed through the aggregates. Although the good bonding between the hardened cement paste and lightweight aggregate such behavior can result in a more linear ascending branch of the stress–strain curve, it does not affect the modulus of elasticity of concrete. It is known that the main disadvantage of lightweight concrete is the significant loss of modulus of elasticity compared to the reduction of compressive strength. Modulus of elasticity of concrete is a function of the modulus of elasticity of the constituents (i.e. hardened cement paste and concrete). Unlike normal concrete, lightweight aggregate is the weakest link in lightweight concretes and as seen in Fig. 3, substantially lower values of modulus of elasticity were obtained as the expanded perlite content increases.

Modulus of elasticity of concrete is an important parameter used in the structural design of concrete structures and there are several models available for the prediction of this parameter. Fig. 3 also shows the values obtained by the expression given in ACI 213 [15]. It can be concluded that the ACI relationship fairly good predicts the modulus of elasticity of concrete when expanded perlite is used.

3.4. Thermal conductivity

Thermal conductivities of the lightweight concretes are shown in Fig. 4. Since moisture content affects the thermal diffusivity, all the specimens were tested in oven-dry condition [23]. Replacing normal aggregate by the expanded perlite reduced the thermal conductivity of the mixtures as a result of the porous structure of the perlite. This reduction is relatively small for the replacement ratios of 20% and 40%. For higher replacement ratios, however, more substantial reductions were recorded. For example, the thermal conductivity of the mixture containing 40% expanded perlite is 12% lower compared to that of the reference mixture, but this ratio is 65% for the mixture with 80% perlite.

Thermal conductivity of a material is the quantity of heat transmitted through a unit thickness in a direction perpendicular to a surface of unit area, due to an unit temperature gradient under given conditions. Porosity is one of the factors affecting the thermal conductivity of concrete and enclosed pores reduce the conductivity due to low thermal conductivity of air. Replacing normal aggregate with the expanded perlite increases the total porosity of concrete which affects the thermal conductivity [24]. Air entrainment might have also contributed to reduce the thermal diffusivity of all the mixtures. As seen in Fig. 4, there is a strong relationship ($R = 0.98$) between the unit weight and thermal conductivity of concrete. The low thermal diffusivity and low unit weight, combined with the ability to cast in any desired shape, enables the lightweight concrete to be a very suitable material for using as building blocks or partition walls.

3.5. Water absorption and sorptivity

Water absorptions of the specimens were obtained by immersing in water until constant weight is reached. The specimens are then oven dried to obtain the water absorption value. As the expanded perlite content is increased, unit weight is reduced and much higher water absorptions are obtained (Fig. 5). Down to a unit weight of approximately 1000 kg/m^3, the increase in water absorption seems constant, however, for higher perlite contents (thus lower unit weights), more substantial increases were obtained. The

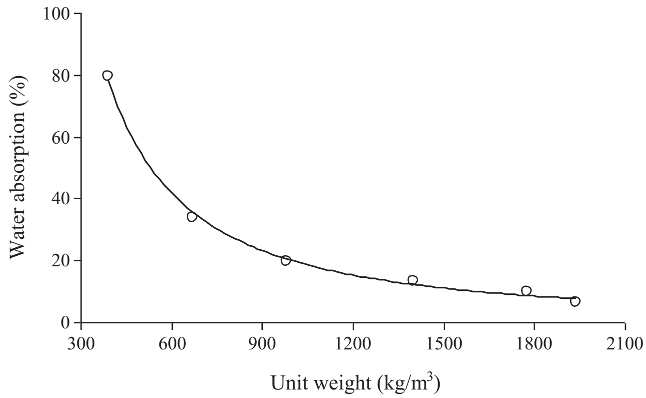

Fig. 5. Effect of expanded perlite aggregate on water absorption.

expanded perlite is a porous aggregate and as mentioned above, the water absorption of the expanded perlite is 310% which have significantly contributed to the water absorption of the lightweight concrete. As seen in Fig. 5, the water absorption of the mixture containing 80% expanded perlite is more than two times higher compared to that with 40% perlite. In this study, the natural sand was replaced by the expanded perlite and since the perlite is coarser than the sand, a more porous structure might be obtained which might have contributed to the higher water absorption and as seen in the figure, for perlite contents more than 60%, the rate of the water absorption increased more significantly.

The high water absorption can affect the durability of the mixtures since most of the aggressive substances are transported into concrete with water [25]. Therefore, from a durability point of view, the high water absorption of the expanded perlite concrete is an important disadvantage and adequate measures should be taken. Coating the surface of lightweight concrete by commercially available water proofing materials may prevent the capillary absorption of water. However, it should be kept in mind that such measures result in extra cost.

Fig. 6 shows the sorptivity (capillarity) coefficient of the lightweight concretes and capillary sorption of the concretes also increased with the expanded perlite content. The rate of this increase seems constant from the unit weights of 1800 to 700 kg/m^3. For the mixture produced with 100% expanded perlite, there is a higher capillary suction. As seen in Fig. 6, the porous expanded perlite aggregate clearly affects the sorptivity of concrete. However, when Figs. 5 and 6 are compared, it seems that the water absorption is affected much more than the sorptivity by the use of higher amounts of expanded perlite. Pores in the expanded perlite act as air voids and reduces capillary suction, but these pores increase the water absorption. Thus, for higher expanded perlite contents, the sorptivity is not affected much as the water absorption.

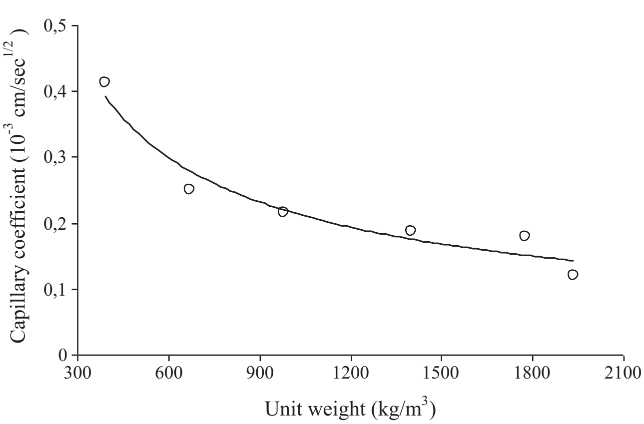

Fig. 6. Effect of expanded perlite aggregate on sorptivity coefficient.

4. Conclusions

The following conclusions could be drawn from the results obtained in this study:

(1) The thermal conductivity of the mixtures is substantially reduced by replacing normal aggregate with the expanded perlite. A strong relationship between thermal conductivity and unit weight was obtained.
(2) Compressive strength and modulus of elasticity of concretes are reduced as the content of the expanded perlite increases. Loss of modulus of elasticity is more substantial compared to the loss in strength. Due to strength loss, concretes produced in this study with more than 20% expanded perlite can be classified as insulation concretes.
(3) Unit weight of concrete can be reduced significantly by replacing natural aggregate by the expanded perlite. In this study, the air dry density of the concrete was reduced to a minimum of 392 kg/m^3.
(4) Both water absorption and sorptivity increase with higher expanded perlite amount. However, it seems that the sorptivity is less affected by the perlite replacement.

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References

[1] S. Chandra, L. Berntsson, Lightweight Aggregate Concrete, Noyes Publications/William Andrew Publishing, NY, 2002, p. 367.
[2] P.A. Ciullo, Industrial Minerals and Their Uses, Noyes Publications, 1996, p. 580.
[3] B. Berge, The Ecology of Building Materials, Architectural Press, 2001, p. 474.
[4] Industrial Raw Materials Commission – Construction Materials, State Planning Organization, Report No. 2617/628, Ankara, 2001, Turkey, ISBN:975-19-2852-4, 73pp (in Turkish).
[5] O. Sengul, C. Tasdemir, M.A. Tasdemir, Influence of aggregate type on the mechanical behaviour of normal and high strength concretes, ACI Materials Journal 99 (2002) 528–533.
[6] ASTM C 330/330M, Standard Specification for Lightweight Aggregates for Structural Concrete, ASTM, West Conshohocken, 2009, 4pp.
[7] ASTM C 332, Standard Specification for Lightweight Aggregates for Insulating Concrete, ASTM, West Conshohocken, 2009, 3pp.
[8] P. Lura, D.P. Bentz, D.A. Lange, K. Kovler, A. Bentur, Pumice aggregates for internal water curing, in: International RILEM Conference on the Advances in Concrete through Science and Engineering, Evanston, IL, 2004, pp. 137–151.
[9] L.H. Yu, H. Ou, L.L. Lee, Investigation on pozzolanic effect of perlite powder in concrete, Cement and Concrete Research 33 (2003) 73–76.
[10] S. Urhan, Alkali silica and pozzolanic reactions in concrete. Part 2: observations on expanded perlite aggregate concretes, Cement and Concrete Research 17 (1987) 465–477.
[11] V.M. Malhotra, Role of supplementary cementing materials in reducing greenhouse gas emissions, in: O.E. Gjørv, K. Sakai (Eds.), Concrete Technology for a Sustainable Development in the 21st Century, E&FN Spon, London, 2000, pp. 226–235.
[12] ACI Committee 122 Guide to Thermal Properties of Concrete and Masonry Systems, ACI 122R-02, 2002, Detroit, 21pp.
[13] R.T. Bynum, Insulation Handbook, McGraw Hill, 2001, p. 512.
[14] J.L. Clarke, Structural Lightweight Aggregate Concrete, Blackie Academic & Professional, 2005, p. 161.
[15] ACI Committee 213, Guide for Structural Lightweight Aggregate Concrete, American Concrete Institute, ACI 213R-03, 2003, Detroit, 38pp.

[16] M.A. Tasdemir, C. Tasdemir, S. Akyuz, A.D. Jefferson, F.D. Lydon, B.I.G. Barr, Evaluation of strains at peak stresses in concrete: a three phase composite model approach, Cement and Concrete Composites 20 (1998) 301–308.
[17] M.L. Torres, P.A. García-Ruiz, Lightweight pozzolanic materials used in mortars: evaluation of their influence on density, mechanical strength and water absorption, Cement and Concrete Composites 31 (2009) 114–119.
[18] T.Y. Lo, W.C. Tang, H.Z. Cui, The effects of aggregate properties on lightweight concrete, Building and Environment 42 (2007) 3025–3029.
[19] P.K. Mehta, P.J.M. Monterio, Concrete, Prentice Hall, New Jersey, 2006, p. 684.
[20] A.M. Brandt, Cement-based Composites, E&FN Spon, London, 1995, p. 536.
[21] A.M. Neville, Aggregate bond and modulus of elasticity of concrete, ACI Materials Journal 94 (1997) 71–74.
[22] M.H. Zhang, O.E. Gjorv, Mechanical properties of high-strength lightweight concrete, ACI Materials Journal 88 (1991) 240–247.
[23] M.I. Khan, Factors affecting the thermal properties of concrete and applicability of its prediction models, Building and Environment 37 (2002) 607–614.
[24] R. Demirbog, R. Gul, The effects of expanded perlite aggregate, silica fume and fly ash on the thermal conductivity of lightweight concrete, Cement and Concrete Research 33 (2003) 723–727.
[25] M. Lanzo, P.A. Garcia-Ruiz, Lightweight cement mortars: advantages and inconveniences of expanded perlite and its influence on fresh and hardened state and durability, Construction and Building Materials 22 (2008) 1798–1806.