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A Review on Investigation of Perlite Based on Its Mechanical and Thermal Properties

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ABSTRACT

This paper deals with a review on investigation of perlite based on its mechanical strength and its thermal property. The investigation shows that the perlite has the property of lightweight due to its porous nature and can be partially replaced with sand since it contains SiO_2 content to a great extent. Due to its porous nature, the researchers say that the perlite in concrete induces thermal insulation property for which the increase in the perlite content decreases the thermal conductivity. But with increase in perlite content, there is a subsequent decrease in the mechanical strength of concrete. This paper consolidates different testing carried out to determine the performance of perlite in concrete in terms of strength and thermal properties.

Keywords: *CSH gel, EPA, LFPs, perlite, silica fume*

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INTRODUCTION

Perlite is a volcanic glass that contains high water content, formed by the hydration of hot molten lava. It has the unusual property of expanding to a greater extent when heated sufficiently. These are used as both industrial and commercial product purpose for its low density. There are two forms of perlite, namely expanded and unexpanded forms. Perlite in concrete induces lightweight nature as it reduces the weight and also thermal conductivity but subsequently it decreases the strength of the concrete.

Effects of silica fume (SF) and expanded perlite (EP) addition on the technical properties of the fly ash (FA)–lime–gypsum mixture shows the combined effects of the porous perlite and the increased cellular calcium silicate hydrate (CSH) gel formation by SF addition that leads to lower thermal conductivity values in FA–lime–gypsum mixture [1]. Effects of EP on mechanical and thermal conductivities of lightweight concrete depict that the concrete improves in its quality by improving the cement quality and dosage of expanded perlite aggregate (EPA) [2]. Impact response of lightweight mortars containing EP concludes that the lightweight mortar that contains EP reinforced with polymer microfibers affects the flexural stress rate sensitivity [3]. Thermal properties of lightweight dry-mix shotcrete containing EPA show that dry-mix concrete up to 75% of replacement of sand with EPA offers superior thermal

properties without affecting its mechanical performance [4]. Effect of perlite on thermal conductivity of self-compacting concrete explains that, with reduction in *k*-value, there is a decrease in the thermal gradient developed in the rigid pavement. This helps in preventing premature cracking due to temperature variation in pavement [5].

An experimental study on lightweight concrete using perlite proves that the lightweight concrete containing 10% perlite replacement shows an increase in the strength parameters [6]. In application of EP-encapsulated bacteria and growth media for self-healing concrete, healing was done in a moist environment for 165 days. It is absolute that faster healing can occur in a wet/dry environment [7]. Characterization of lightweight ferrocement panels containing EP-based mortar explains that the ultimate strength and deflection of LFPs (local field potential) were based on the increase in the number of wire mesh layers, reinforcement surface area, yield strength of wire mesh, diameter of wire mesh and cement content. The pozzolanic activity of EP particles was affected by higher particle size and water absorption when compared to that of ordinary cement concrete [8]. Compressive strength and corrosion evaluation of concretes containing pozzolana and perlite immersed in aggressive environments proved that the replacement of 20% and 30% of pozzolana and perlite has a negative effect on corrosion in the aggressive medium. For sulfate attack, it is seen that values of E_{corr} (electrochemical corrosion) are low. This means that the sulfate ions did not affect the concrete by corrosion activity during the testing period [9].

Development and thermal performance of an EP-based phase change material wallboard for passive cooling in building indicated that phase change material room (PCMR) in concrete resulted in smaller temperature fluctuation, lower peak temperature and larger lagging time when compared to that of reference room, especially PCMR under the operation strategy of natural convection operation with temperature (NCTE). The qualified thermal performance showed significant application potential for composite phase change material wallboard (CPCMW) incorporated with building envelope to passively adjust the indoor air temperature and increase the thermal mass of the building, especially for lightweight building [10]. Effect of EPA on the properties of lightweight concrete is a research work carried on, from which it was observed that the compressive strength, splitting-tensile strength and the dynamic elasticity modulus increased with the increase in dosage. However, workability was considerably affected by the cement types and dosages. It was proved that EPA can be used as fine aggregate in concrete with appropriate replacement ratios along with the lightweight property [11]. Effects of EPA and different curing conditions on the physical and mechanical properties of self-compacting concrete show that the apparent porosity for curing condition-2 (CC2) increased more than the other conditions by increasing EPA ratio for 28-day curing period. The changing of capillarity coefficient values depends on the curing time, curing condition and the percent of EPA [12]. Effects of EPA and mineral admixtures on the compressive strength of low-density concrete prove that the EPA increased the 28-day compressive strength up to 108% with 60% EPA replacement of PA, while it increased the 7-day compressive strength up to 85% with 40% EPA replacement. The effect of EPA increased with increasing curing period. SF is more effective and increased the 28-day compressive strength at all levels of SF, especially at 20% SF. The maximum increment was 69% with increasing EPA,

the effect of SF decreased, and with increasing curing time, the effect of SF increased [13]. Effect of EPA on cyclic thermal loading of HSC and artificial neural network modelling determined that, at the end of 300 cycles, the calculated durability factors of HSCs with 10%, 20% and 30% EPA are more than 60%. The result of the testing phase shows that the NN is capable of generalizing between input variables and the output (compressive strength and UPV values) [14]. Experimental and numerical investigation of a hollow brick filled with perlite insulation depicts that the modern hollow bricks filled with perlite characterize high thermal resistance and can be applied without any additional insulation layer. In this case, total *U*-value of a wall is lower than 0.29 W/m^2K. The perlite insulation has often been damaged on the construction site most likely during the manual handling of the bricks. This incorrect practice of the brick layers can increase the penetration of mortar into the spaces and, as a consequence, thermal energy consumption will increase.

STRENGTH AND THERMAL EFFECTS WHILE ADDING PERLITE IN CONCRETE

Sengula et al. [2] provided data on effects of EP on thermal conductivity and mechanical properties of lightweight concrete. Here, an EP obtained from Bergama-Izmir, located in the west region of Turkey, was used. The perlite used consists 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 an experimental study, locally available natural sand with a specific gravity of 2620 kg/m^3 was also used. Particle size distributions of the EPA and natural sand are given in Table 1 [2]. As seen from the table, the EP 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), super-plasticizer and air entraining admixture were used in all the mixtures.

Table 1. *Aggregate grading [2].*

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

Standard tests were done in accordance with European Standards (EN 206 and EN 12390). Three 70-mm cubes were used for the standard compressive strength of the concrete. Three cylinders of 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 the stresses below approximately 30% of the ultimate strength. 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.

Lightweight concrete can be classified into different groups based on its unit weight and compressive strength. 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 strength, mixtures containing more than 20% EP can be classified as insulation concrete. 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 strength 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. The properties of these constituents affect the properties of concrete, thus, as the normal aggregate is replaced by the porous EP, compressive strength of concrete is reduced due to lower strength of the perlite. The air entrainment also contributed to the low strength of the concrete.

Since moisture content affects the thermal diffusivity, all the specimens were tested in oven-dry condition. Replacing normal aggregate by the EP reduced the thermal conductivity of the mixture as a result of the porous structure of perlite is obtained. 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% EP is 12% lower where compared to that of the reference mixture, but this ratios 65% for the mixture with 80% perlite.

From Liu et al. [4], the EPA, type GU Portland cement and sand were locally sourced in Edmonton. The EPA was mainly composed of SiO_2 (70%–75%) and Al_2O_3 (12%–18%). It had a porous structure with a bulk density of 71 kg/m^3 in oven-dry conditions, it was rated to absorb water at 100% of its dry mass. The sand was at saturated surface dry (SSD) condition, corresponding to a moisture content of 2.04% by mass. It had a bulk density of 1675 kg/m^3 in oven-dry (OD) conditions. The mixes were designed in accordance with ACI 506.5R-09, and the sieve analysis of the EPA and the sand used along with their blends were conducted as per ASTM C 126 by means of a mechanical shaker. The grain size distribution for the aggregate blends in all the mixes in each case, within the shotcrete grading zone No. 1 given in ACI 506R-05. Besides the reference mix with no EPA, four other mixes were produced in which sand was replaced with EPA at four levels of volumetric substitution, namely 25%, 50%, 75% and 100%.

The method of thermal evaluation can be divided into two categories, namely steady-state method and transient method. In the former, the heat flow through the samples is controlled to let the temperature gradient over a measured distance that achieve steady state. However, the process to reach steady state usually takes a long time, and these methods provide thermal conductivity after a period of 2–3 h. On the other hand, in transient method, one records the signal change with time even with the sample is being heated. As a rule, these allow quicker evaluation of the thermal constants usually within minutes. Among the transient method, the transient plane source (TPS) method has been recognized as a standard for almost 10 years, and it is valid for thermal conductivity over a wide range from 0.005 to 500 W/mK. This technique was developed by Gustafson during the 1990s and it is being used widely to characterize the thermal properties of construction materials. It is found to yield rapid and simultaneous information on the thermal conductivity and thermal diffusivity. The average transient temperature increase (T) on the bifilar spiral of Kapton probe has been given as the exact analytical solution as follows:

$$\Delta\overline{T} = P_o(\pi^{3/2} rk)^{-1} D(\tau) \quad \text{..... [4]}$$

where ΔT is the average transient temperature increase (K); P_o is the output power (W); r is the radius of the Kapton probe (mm) and k is the thermal conductivity of the testing sample (W/mK). Also, $D(\tau)$ details of the expression are provided as follows:

$$D(\tau) = \frac{1}{m^2(m+1)^2} \int_0^{\tau} \frac{d\sigma}{\sigma^2} \sum_{i=1}^{m} k \sum_{j=1}^{m} i.e.^{-\left(\frac{i^2+j^2}{m^2}\right)/4\sigma^2} \times I_0\left(\frac{ij}{2m^2\sigma^2}\right) \quad \text{[4]}$$

where σ is the integration variable; I_0 is the modified Bessel function; *e* is the base of natural exponential function; and *m* is the number of concentric rings in the Nickel bifilar spirals. Both thermal conductivity and thermal diffusivity were obtained by this single TPS test by means of the data. There was a drop in this parameter with an increase in the EPA replacement. Given that EPA has a thermal conductivity of 0.04 W/mK compared with a value of 0.78–2.2 W/mK for sand, it is clear that an increase in EPA content should result in lower thermal conductivity. More moisture is trapped when concreting as against during casting in the conventional manner. This is especially true at higher EPA contents and can be noticed that there was a decrease in thermal diffusivity with an increase in the EPA content. Once again, when compared with results obtained with conventionally cast mixes made with identical proportions, it appears that concreting resulted in higher thermal diffusivity, and this may again be attributed to the higher water demand associated with EPA.

Due to the inherent lack of control over the water content (and consequently, on the water–binder ratio) in shotcrete produced through the dry-mix process, there is more merit to compare the UCS values against the oven-dry density, as compared to the air-dry density. Although the two processes result in the products with varying density, it is clear that the UCS in both cases obeys a similar trend with oven-dry density. The trend so obtained can be attributed to the porous microstructure of EPA itself, and possibly, a weaker interfacial transition zone influenced by the introduction of EPA. As expected, the only significant difference in the UCS as a result of the concreting process was seen with mix SP100, which is at a particular difference in its oven-dry densities. The data from the shotcrete samples suggest a nonlinear relationship with a 0.9 power. The difference seen between the sprayed and cast mixes may be attributed to a transverse isotropy and superior consolidation in the former, an explanation that is consistent with research on self-compacted concrete wherein a power-law with an exponent of 1.04 was obtained.

From Gandage and Rao [5], the property that characterizes the ability of the material to transfer heat is thermal conductivity (*k*). It is a specific property of the material. *k* is a measure of the rate at which heat (energy) passes perpendicularly through unit area of a homogenous material of unit thickness for a temperature difference of one degree. Thermal conductivity measurement is important to understand the heat flow in cement concrete pavements. There are two main methods to measure thermal conductivity of materials, namely the steady-state method and the transient method. Steady-state methods are adopted for homogeneous materials. In this method, the flux is proportional to the temperature gradient along the direction of flow. The experimental procedures are time consuming; however, the thermal conductivity values obtained by this method are accurate. The transient analyses are the non-steady methods adopted for heterogeneous materials with moisture. Though the test procedures are relatively fast, the accuracy of the *k*-value is less. The common methods adopted for transient analysis are laser flash method, step method, transient line, transient strip and transient plane method. In the present study, steady-state method has been adopted to measure the thermal conductivity values. The guarded hot-plate method (ASTM C177), as recommended in ACI 122R, has been adopted for the present study. This is a commonly used test method for measuring thermal conductivity of cement concrete for pavement applications. The thermal conductivity of concrete governs the rate of heat flow through the concrete structure.

The main factors that influence the thermal conductivity of concrete are mineralogical characters of the aggregates, cement content, water content, and air void content along with temperature and moisture condition of concrete. Of the above-mentioned factors, the important factors that govern the thermal conductivity of concrete are the mineralogical characters of the aggregate and the exposure of concrete to moisture conditions. Concrete prepared with siliceous aggregates have higher thermal conductivity than concrete prepared with carbonate aggregates. Addition of lightweight aggregate materials like perlite helps reduce the *k*-values. The thermal conductivity of water is much higher than air. Hence, the thermal conductivity of moist concrete will be more than the dry specimen. Cement content in the concrete mix also influences the *k*-values.

Increase in cement content increases the thermal conductivity. Powder additions (like FA, slag) help lower the *k*-values by reducing the cement content. Of all the powder additions, FA is more effective in reducing the thermal conductivity values of concrete. For different additive combinations for M-40 grade SCC mix, the thermal conductivity test had been conducted; Figure 1 shows the result.

Thermal studies on cement concrete are important for rigid pavement analysis. The thermal stresses influence the joint spacing and design of temperature reinforcements for rigid pavements. The powder-based SCC mix ensures a homogenous and dense matrix with minimum risk of segregation. From the test results on mechanical properties, it is observed that all the specimens satisfy the 28-day flexural strength criteria of 4.5 MPa.

Hence the optimal value of perlite dosage has been decided on the basis of 28-day compressive strength. From the studies undertaken, it is observed that 5% perlite dosage gives a maximum 28-day compressive strength of 51.852 MPa (28-day flexural strength of the said mix is 8.4 MPa). Hence, 5% perlite dosage is preferred perlite dosage from the strength perspective. Addition of FA and perlite brings down the density of the mix. The thermal conductivity values of the concrete mix decrease at all temperature ranges, with decrease in density. At lower temperature, the *k*-values are higher as compared to the *k*-value at higher temperature. This is attributed to the fact that the residual moisture present in the concrete specimen gets dried up with increase in temperature. Hence, the *k*-value decreases at higher temperature. Usually in Indian conditions, the peak pavement surface temperature is in the range of 50°–60°C during summer season.

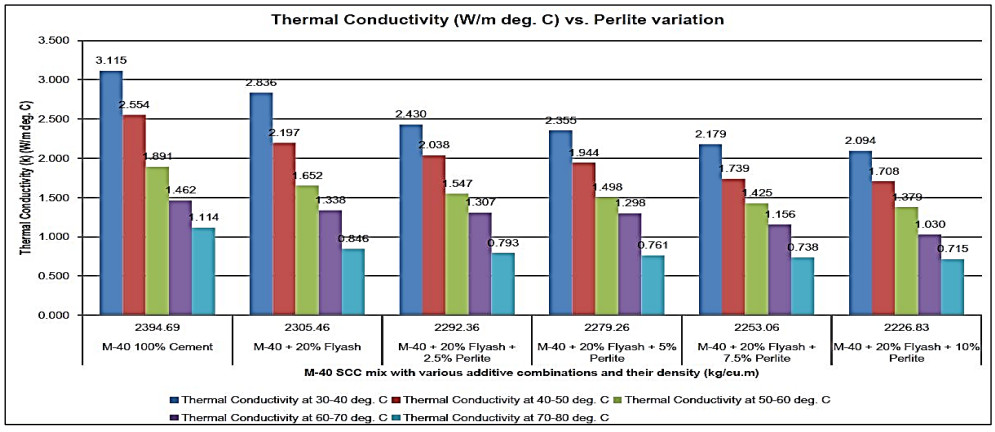

Fig. 1. *Results of thermal conductivity test for various additive combinations for M-40 grade SCC mix [5].*

It is observed that addition of FA (Mix 2) alone brings down the *k*-value by 12.64% as compared to the k-value of Mix 1 at 50°–60°C range. The *k*-value of M40 SCC mix with 20% FA and 5% perlite is 20.78% lower than the *k*-value for M40 SCC mix with 100% cement at a temperature range of 50°–60°C. The reduction in *k*-value decreases the thermal gradient developed in the rigid pavement. This helps in preventing premature cracking of pavement on account of temperature variation.

From Kong and Yao [10], an important point of PCM used in building was the suitable phase change temperature range and enough latent heat capacity, especially for PCM used in the internal building envelope. A kind of paraffin produced by Nanyang Wax Fine Chemical Company was used to be the phase change material, which has large latent heat. Besides, its onset melting is within the range of human body comfort. In order to improve the comfort of human body in buildings in the premise of reducing energy consumption, the materials fabricated by encapsulating the paraffin with supporting materials were incorporated with the building envelope, to passively adjust the indoor temperature. The adsorption method, which refers to encapsulate PCM by the supporting material, is commonly used to prepare the phase change material. Generally, the supporting material should have a large number of micro-pores and certain strength to firmly contain PCM. In this study, the EP, whose size is 3–6 mm, was selected to be the supporting material to fabricate the phase change material particle. EP is mainly composed of SiO_2, Al_2O_3 and Na_2O, which account for more than 90% of the total mass, and a small amount of MgO, GaO, etc. Because it has porous structures and larger specific surface area, PCM particle (PCMP) can be prepared through liquid paraffin adsorbed into EP, with the capillary effect of micro-pores and the surface tension under the vacuum condition.

PCM used in buildings can enhance indoor thermal comfort and decrease building energy consumption. A kind of shape-stabilized PCMP was prepared by liquid paraffin to be absorbed into the micro-pores of EP with a self-made vacuum heating rolling box. A novel CPCMW was fabricated by PCMP, styrene acrylic emulsion and glass fibers under a plate-shaped mold. The properties including thermal property, internal microstructure and mechanical property have been characterized by differential scanning calorimeter (DSC), scanning electron microscope (SEM) and electronic universal testing machine. The cold storage performance of CPCMW was experimentally studied in two rooms with the same size, under the summer condition. CPCMW was incorporated with the inside surface of wall and ceiling in a room, which was called PCM room (PCMR); while the other one without PCM was addressed as reference room. Besides, three operation strategies, i.e., natural convection operation with time (NCTI), NCTE, and cold storage in closed building, were conducted in experiments. In DSC test, the melting point and latent heat of CPCMW were 25.22°C and 85.63 J/g, respectively. In frames and electronic universal testing machine analyses, it was found that CPCMW had a compact and firm microstructure, and good strength and toughness. Based on the comparison data of PCMR and reference room in the experiment of cold storage, CPCMW showed a satisfied thermal performance, especially with the operation strategy of NCTE. It can be concluded that the novel CPCMW has a significant opportunity for building application.

PCMP was prepared by EP to adsorb liquid paraffin through a self-made vacuum heating rolling box, and then CPCMW was

fabricated by further pressing the PCMP in a plate-shaped mold. Properties of CPCMW have been characterized by DSC, SEM and electronic universal testing machine. The cold storage ability of CPCMW was experimented in two same-size rooms, i.e., PCMR and reference room, and both rooms didn't install the space cooling system. In PCMR, CPCMW was incorporated with the wall and ceiling; while no PCM was installed in reference room. The results indicated that PCMR had smaller temperature fluctuation, lower peak temperature and larger lagging time than that of reference room, especially PCMR under the operation strategy of NCTE. The qualified thermal performance has showed significant application potential for CPCMW incorporated with building envelope to passively adjust the indoor air temperature and increase the thermal mass of building, especially for lightweight building. However, limited by the existing experimental conditions, some important points have not been finished, including the operation strategy with space cooling system, the thermal performance in winter, and thermal storage capacity enhancement.

From Karakoç et al. [14], artificial neural network (ANN) techniques open new possibilities in classifying and generalizing available experimental results, through learning by example to predict strength from the relative content of mix components. If such a mapping can be effectively modelled in a neural system in spite of data complexity, incompleteness and incoherence, it might be useful in concrete mix design as a new tool to support the decision process and improve efficiency. The feed-forward architecture, also known as the multilayer perceptron, is the most popular network architecture used by researchers in various structural material characterization and modelling studies. They use the BP algorithm to predict the thermal and mechanical properties of composite materials. The BP algorithm also has been used for composite material characterization, constitutive modelling of concrete, viscoelastic materials and to model concrete workability in design of high performance concrete mixtures. Portland cement (CEM I 42.5) was utilized in preparing the concrete specimens. SF and EPA were obtained from the Antalya Electro Metallurgy Enterprise, and the ETI Bank Perlite Expansion Enterprise, respectively, in Izmir, Turkey. The chemical composition of the materials used in this study is summarized in Table 2. The physical and mechanical properties of Portland cement and the physical properties of EPA are summarized similarly in Tables 3 and 4, respectively. The specific gravity of SF and EPA was 2.20 and 0.28, respectively. The percentages of EPA that replaced fine aggregate (0–2 mm) in this study were 0%, 10%, 20% and 30%. The used w/b (water–binder) ratios were 0.25, 0.30 and 0.35. In addition, a group sample with an air entraining agent (AEA) was used for each w/b ratio. The binder dosage and the dosage of SF were kept constant at 500 kg/m^3 and 7% (by weight of binder), respectively, throughout the study. A modified polycarboxylate-based polymer was used as a super-plasticizer, which conformed to Type F of ASTM C494 (high-range water reducer), at a dosage of 2.0, 1.50 and 0.75 ml/kg of cement, for 0.25, 0.30 and 0.35 w/b ratios, respectively.

The NN model developed in this research is used to predict the compressive strength values of the HSC mixture data. Inputs are w/b, C, EPA, and the output is the relative change in compressive strength (RCCS). The result of the testing phase shows that the NN is capable of generalizing between input variables and the output (compressive strength values).

Results of model performance levels during training and test stages are given as follows: the R^2 value is 98.07% for UPV values.

Table 2. *Chemical composition of PC, SF and EPA(%) [14].*

Component	PC	SF	EPA
SiO_2	19.6	93.7	71–75
Al_2O_3	4.77	0.3	12–16
Fe_2O_3	2.91	0.35	–
CaO	62.00	0.8	0.2–0.5
MgO	3.2	0.85	
SO_3	2.69	0.34	0.15
C	2.69	0.52	
Na_2O	0.35	–	2.9–4.0
K_2O	0.53	–	
Chloride (Cl^-)	0.0082	–	0.09
Sulphide (S^{-2})	0.1	0.1–0.3	
Undetermined	0.38		
Free CaO	0.25		

Table 3. *Physical and mechanical properties of PC.*

Specific gravity (g/cm^3)		3.10
Specific surface (cm^2/g)		3389
Setting time initial (min)		170
Volume expansion (mm)		2
Compressive strength (MPa)	2 days	28.6
	28 days	53.4

Table 4. *Physical properties of EPA.*

Color	White
Unit weight	30–190 kg/m^3
Porosity	90%
Specific heat	0.20–0.23 kCal/kg °C
Melting point	1300 °C
Thermal conductivity	0.039–0.046 W/mK
Thermal expansion	0.004–0.011 mm/m °C

All statistical values demonstrate that the proposed NN model is suitable and predicts compressive strength values very close to experimental values. A small perceptible deviation is observed for the calculated values. Also, the model found with the genetic algorithm was given. Finally, results from the genetic algorithm in order to determine optimum mix proportions to compute minimum relative change (RC), subjected to 300 thermal cycling.

EPA and AEA decreased the fresh unit weight when compared to control samples. At the end of 100 cycles of freeze–thaw, 10% EPA increased the compressive strength of the samples 2%, for 0.30 w/b ratio, according to control samples. From

the data presented, we see that the optimum amount of EPA used to improve freeze–thaw cycle resistance is 10%. The resulting capillary pore volume of the EPA mixture is larger than that of the reference mixture. The measured porosity values increased after 300 cycles of freeze–thaw. The RDME of samples decreased with an increase in EPA replacement percentage, after 100, 200 and 300 cycles of freeze–thaw for all w/b ratios. It was determined that at the end of 300 cycles, the calculated durability factors of the HSCs with 10%, 20% and 30% EPA were over 60%. The reduction in RDME of samples with 10% EPA was less than in the control samples. Hence, it can be concluded that when 10% EPA is added to HSC, its frost resistance can be raised. The result of the testing phase shows that the NN is capable of generalizing between input variables and the output (compressive strength and UPV values).

From Demir and Baspinar [1], ETI Bank Perlite Enterprise in Izmir and Antalya Electro Metallurgy Enterprise in Turkey, respectively. FA is appropriate to the C class according to ASTM C 618, since total oxide of SiO_2+Al_2O_3 + Fe_2O_3 is higher than 70% and CaO is less than 10%. The mineral composition of the FA is mainly quartz, mullite and albite. Commercial grade slaked lime and gypsum (ABS) were used in the experiments. The chemical composition of the FA, EP and SF is given in Table 5. The particle size distribution of the FA, SF and EP was measured with Laser Size Distribution Analyzer-Master Sizer X1.2b.

Effect of the super-plasticizer addition was investigated. Super-plasticizer addition increased the strength values for all series because of the decrease in water/solid ratio. However, strength increment in low gypsum containing and low CaO:SiO_2 series (K7–K9 series) was much more than the high gypsum containing series (K1–K6 series). This is possibly due to the lower available water content for the setting of the hemi-hydrate-type gypsum which has also contribution to the strength of the system. Super-plasticizer addition was found to be useful for the strength in cement of the mixtures and adjustment of the workability of the FA–lime–gypsum system. It was explained that the super-plastics do not react by a chemical action on hydrated products; they affect the microstructure of cement gel and concrete, and the porosity decreases significantly. Strength losses due to the expansive ettringite formation.

Table 5. *Chemical analyses of fly ash (FA), silica fume (SF) and expanded perlite (EP) [1].*

Component	FA (% wt)	SF (% wt)	EP (% wt)
SiO_2	54.20	94.50	73.16
Al_2O_3	21.10	0.88	12.87
Fe_2O_3	9.40	0.70	0.88
CaO	4.40	0.80	0.85
MgO	4.20	1.25	–
K_2O	2.10	–	4.76
Na_2O	0.68	–	2.35
SO_3	0.51	–	0.29
Loss on ignition	2.90	0.75	2.58

Replacing SF instead of FA increased the thermal conductivity of the mixture and the bulk density at high gypsum mixture. SF addition to the FA–lime–gypsum mixture was found to be useful for the improvement of the pozzolanic reactions and the formation of cellular CSH structures. However, optimized SF addition level

should be investigated for prevention of the strength reduction due to the expansive crystalline phase formations such as ettringite, especially at high gypsum content. Perlite addition to the FA–lime–gypsum mixture decreased the bulk density and the thermal conductivity. Simultaneous addition of SF and perlite at low gypsum containing mixture results in the lowest thermal conductivity. The combined effect of the porous nature of perlite and the increased cellular CSH gel formation with SF addition results in lower thermal conductivity values in FA–lime–gypsum mixture. Steam curing and super-plasticizer addition are found to be useful for the strength increment of the FA–lime–gypsum mixture.

From Bhuvaneshwari et al. [6], the cement used for this experimental study is 43 grade ordinary Portland cement. All properties of cement are tested by referring IS 12269-1987. Perlite is an amorphous volcanic glass that has relatively high water content. It occurs naturally and has the property of highly expanding when heated sufficiently. It is an industrial mineral and a commercial product useful for its lightweight after processing; the product expands 4–20 times its original volume. Perlite expansion is due to the presence of 2%–6% combined water in the crude perlite rock. When the crude oil is quickly heated to above 8700°C (16,000°F), the product pops in a similar manner to popcorn. Good-quality natural river sand is used as fine aggregate.

The sand is sieved in 2.36-mm sieve as the sand passing through this sieve is used as fine aggregate. Zone of the fine aggregate used in this work is zone II. Hard granite broken stone was used as coarse aggregate. The coarse aggregate is sieved in 20-mm sieve and the aggregate passing through the sieve is used as coarse aggregate. Clean potable water conforming to IS 456-2000 was used in the preparation of the concrete. The qualities of water samples are uniform. The pH of water lies between 6 and 8 and the water is must be free of all acids, bases and other dissolved salts. A super-plasticizer of sulfonated naphthalene formaldehyde was used as an admixture during the mixing of fresh concrete.

150 mm x 150 mm x 150 mm cubes were tested at the age of 7 and 28 days after curing using compression testing machine (CTM). The ultimate load divided by the cross-sectional area of the specimen is equal to the cube compressive strength. Table 6 shows the result of the compression testing.

Table 6. *Results of compressive strength [6].*

Sl. no	Specimen details	Compressive strength (MPa)	
		7 days	28 days
1	Conventional mix	15.64	20.52
2	5% perlite	14.67	19.24
3	10% perlite	13.17	20.90
4	15% perlite	13.80	18.80
5	20% perlite	9.00	12.56
6	25% perlite	6.11	7.49

1.85% increment in the compressive strength is found at 10% replacement of sand by perlite at 28 days when compared to normal concrete.

The tensile strength of concrete is determined with specimen of size 150 mm diameter (D) and 300 mm long (L) at the age of 7 and 28 days after curing using CTM. The split tensile strength of concrete was found using ($2P/\pi LD$), where P is the maximum load on the cylinder. 10.46% increment in the split tensile strength is found at 10% replacement of sand by perlite at 28 days when compared to normal concrete. Table 7 shows the result of the tensile testing.

Flexural strength test was carried out on beam specimens of size 100 mm x 100 mm x 500 mm at the age of 28 days after curing using CTM. The flexural strength of concrete was found using PL/bd^2 or

$3Pa/bd^2$, where P is the maximum load on the cylinder and 'a' is the distance of crack from the nearest support of $a > 20$ cm and $a < 20$ cm, respectively. 10.20% increment in the flexural strength is found at 10% replacement of sand by perlite at 28 days when compared to normal concrete. Table 8 shows the result of the flexural testing.

Table 7. *Results of tensile strength [6].*

Sl. No	Specimen details	Tensile strength (MPa)	
		7 Days	28 Days
1	Conventional mix	1.22	2.39
2	5% perlite	1.47	2.41
3	10% perlite	1.66	2.64
4	15% perlite	1.62	2.50
5	20% perlite	1.71	2.55
6	25% perlite	1.67	2.52

Table 8. *Results of flexural strength [6].*

Sl. No.	Specimen details	Flexural strength (MPa)
		28 Days
1	Conventional mix	5.39
2	5% perlite	5.71
3	10% perlite	5.94
4	15% perlite	5.87
5	20% perlite	5.75
6	25% perlite	5.52

The optimum replacement percentage of sand by perlite is 10%. The compressive, split, tensile and flexural strengths were reduced if the replacement percentage of perlite will be increased.

From Isıkdag [8], the matrix of ferrocement is mortar that consists of cement, sand, water and optionally an admixture. In this study, LFPs were produced with two different mix designs (M1, M2) of EPBM using CEM I 42.5R Portland cement, fine-grained sand, EP, admixture, ordinary drinking water and three types of wire meshes. In mortar production, water/cement ratio was 0.50. EP with grain size of 0–2 mm and bulk density of 60 kg/m^3 was used as aggregate to reduce the weight of LFP mixture, which was used as mortar plasticizer with content of 0.5 kg/m^3 to ensure workability. Thus, the mortar was easily placed in molds despite the small aperture of square wire mesh. The square-woven wire mesh and two types of hexagonal woven wire meshes made of stainless steel were used in LFPs. A sandwich-formed structure was prepared by using one or two layers of wire mesh. In this study, the square wire mesh used in the production of LFPs is named type 1, and has an aperture of 3 mm and a wire diameter of 1 mm. The yield strength of wire used in the fabric is 450 MPa. The square wire mesh has higher yield strength compared to the two types of hexagonal wire meshes used in this study. It also has a flat surface and long service life and is widely used in construction, industry and agriculture. Although square meshes are more expensive and need more labor compared to hexagonal meshes, they led to better results on LFPs at flexural loading tests. The hexagonal wire meshes used in this study are named type 2 and type 3, and they have mesh sizes of 12.7 and 25.4 mm, respectively. In addition, they both have wire diameters of 0.7 mm, and the yield strength of wire used in the fabric was 310 MPa. The hexagonal wire meshes are mostly used in poultry and animal housing and fencing, and they are structurally less efficient than the square wire mesh because of un-oriented wires in principal stress directions.

It was observed that the compressive strength of EPBM-M2 was higher compared to EPBM-M1. Thus, LFP series containing EPBM-M2 had higher resistance under flexural loading compared to that of LFP series containing EPBM-M1. The maximum deflection was 3.5 mm under a load of 7000 N, which was obtained in LFP-D1 containing EPBM-M2. In addition, approximately 40% decrease in compressive strength was found on EPBM when compared to conventional mortar.

The compressive strength and the flexural strength of EPBM-M1 were found as 18 and 4 MPa, respectively. The compressive strength and the flexural strength of EPBM-M2 were found as 20 and 4.5 MPa, respectively. In addition, the hardened unit weights of EPBM-M1 and EPBM-M2 were found as 1800 and 1600 kg/m^3, respectively. However, it was proved that EPBM-M2 had higher compressive and flexural strength despite the lower unit weight when compared to EPBM-M1. This can be explained by the higher cement ratio and the better mix design of EPBM-M2.

The ultimate strength and deflection of LFPs increased as the number of wire mesh layers, specific surface of reinforcement, yield strength of wire mesh, diameter of wire mesh and cement content increased. The period until first cracking and the crack width of LFPs decreased as the number of wire mesh layers and cement content increased. LFP-D series showed better performance compared to LFP-S series under flexural loading. The optimum LFP design was achieved by LFP-D1 containing EPBM2. The types of wire mesh and number of wire mesh layers had no significant effect on the weight of LFPs due to the low total weight of wire meshes used in each LFP. The compressive and flexural strength of EPBM-M2 was higher compared to EPBM-M1. The use of EPBM-M2 in LFPs was found more effective compared to EPBM-M1 due to the lower unit weight and higher strength of EPBM-M2. In SEM analysis of EPBM-M2, the crystal-like, porous and glassy structure of EP was observed, and hydration products were identified. In addition, the atomic ratios of EPBM-M2 found in EDS analysis suggest a likely composition to be closer to the true composition of EP or the hydration products. In XRD analysis of EPBM-M2, minerals such as portlandite, calcite, ettringite and quartz were observed. The low peaks of portlandite suggested low C–S–H formation in the mortar matrix. In BET analysis of EPBM-M2, it was observed that EP caused an increment in the pore size of mortar matrix and also in the amount of larger pores. Moreover, the porous structure of the mortar led to a reduction in unit weight and strength of EPBM. In TG analysis of EPBM-M2, it was concluded that EPBM-M2 had high moisture loss due to the porous structure and high water absorption of EP. In addition, DTA curves exhibited peaks, which refer to the decomposition of ettringite, dihydroxylation of $Ca(OH)_2$ and decomposition of $CaCO_3$, respectively. The low pozzolanic activity of EP was explained by the low amount of amorphous SiO_2 existing in the EP. In addition, the pozzolanic activity of EP particles was adversely affected by the bigger particle size and the higher water absorption of EP when compared to that of cement.

From Fodil and Mohamed [9], Portland cement CEM I class 42.5 from the Lafarge Cement Plant in M'sila is used. The used natural pozzolana is of volcanic origin extracted from the Bouhamidi deposit located at south of Beni-Saf in Algeria. The Blaine-specific surface area of the used natural pozzolans: SSB = 4330 cm^2/g. Its absolute density is ρ = 2.45 g/cm^3. Natural pozzolana was analyzed by X-ray diffraction (XRD). The X-ray elemental spectra of natural pozzolana obtained by scanning electron microscopy/energy-dispersive X-ray analysis confirm the presence of large amounts of silica (Si), moderate amounts of alumina (Al), minor amounts of alkali metals (Na), and some traces of iron (Fe) and calcium (Ca). The mineralogical composition of NP was determined by XRD. The used perlite is a siliceous volcanic rock. The rock is first crushed and calibrated by granulometry. It was extracted from the deposit of Hammem

Boughrara located in Tlemcen, Algeria. The industrial expansion of perlite is carried out by EFISOL in special furnaces, fixed or rotary. Under the effect of heat, the grains of perlite expand: a multitude of closed cells are formed inside the grains. The perlite is used in the form of a sifted powder at 80 lm in all tests. The Blaine-specific surface area of the used perlite is: SSB = 4060 cm^2/g. Concrete mixtures were made using Portland CEM I 42.5N cement and three combinations of binders obtained as a result of partial replacement by weight of the cement with different levels of natural pozzolan and perlite (10%, 20% and 30%). The concretes are intended for the manufacturing of test specimens of diameter 70 mm and length 100 mm.

The compression test was performed according to ASTM C 109/C109M. Cubic concrete samples (70 x 70 x 70) mm^3 with, respectively, 0%, 10%, 20% and 30% of natural pozzolan and perlite to replace cement by mass, the various test pieces of concretes prepared in the laboratory, are kept in the room at a temperature of 20° ± 2°C with a relative humidity greater than 90%. After 24 h, the mold was removed and the samples were stored in saturated water for 28 days (hardening period). After curing the samples in a saturated solution of lime, they were placed in various aggressive media (concentration 5% NaCl and 5% $MgSO_4$), because this concentration is considered a high experimental concentration for accelerated laboratory tests, compared with that of the natural environment. The compressive strengths of the three concrete samples were determined at 7, 14, 28, 60, 90 and 365 days, and the average of the three values was calculated and recorded. Numerous laboratory tests were carried out on specimens in order to obtain accelerated corrosion. The concrete system to be tested consists of a normal concrete without pozzolana and perlite (CC) and three concretes (C10, C20 and C30) containing, respectively, 10%, 20% and 30% of PZ and P by weight of cement. A few cylindrical samples, 70 mm of diameter and 100 mm of height, were cast. A number of steel bars, 10 mm of diameter and 110 mm of length, were incorporated in the center of these samples. Before, they were introduced into the concrete, and then they were partially covered with epoxy resin leaving an exposed surface of 8.64 cm^2. The ends of the steel bars were connected to electrical wires. The samples were directly placed into fresh water, 5% NaCl solution and 5% $MgSO_4$ solution according to ASTM 876-91.

The addition of 10%–20% of finely ground natural pozzolana and its subsequent reaction with cement hydrates provides an effective pore-filling effect (mechanical property). A cement replacement of 10% with pozzolan and 10% of perlite led to an increase in the induction time and reduction of the corrosion rate (corrosion rate decrease) in an environment containing 5% of NaCl during one year. Therefore, the use of natural pozzolan and perlite affects both initiation and propagation time of advances in steel corrosion. A cement replacement of 20% and 30% of pozzolana and perlite, respectively, has a negative effect on corrosion in the aggressive medium. For the sulfate attack, it has been noticed that the values of E_{corr} are low. This means that the sulfate ions did not affect the corrosion activity in the concrete samples throughout the immersion period (365 days).

From Demirbog et al. [13], the concrete strength and other properties heavily depend on its microstructure. The microstructure of concrete depends upon a number of parameters such as type, amount and structure of constituent materials, etc. Constituent materials for concrete include fine as well as coarse aggregates

(traditional or lightweight aggregates), and hydrated cement paste as a binder resulting from hydration or pozzolanic reaction of cementitious materials with water. The structure of concrete is greatly influenced by the rate of hydration or reaction, type of hydration or reaction products formed, and their distribution in the hydrated cement paste. It is well established that the rate of hydration and reaction and the resulting hydration or reaction products can be substantially modified by use of chemical and mineral admixtures. LWCs, made up of lightweight aggregates, have superior properties such as lightness, thermal isolation, freeze–thaw resistance, and fire protection, but have the disadvantage of having low mechanical properties. There are a number of studies related to the effects of SF and FA on the properties of the traditional concretes and concretes made with mixes of traditional and lightweight aggregates. However, there was not enough information about the properties of mixes of different lightweight aggregates and the effects of SF and FA on the compressive strength of these concretes in the technical literature. Most lightweight aggregates used today such as expanded clay, the EPA, and FA have been manufactured at a fringe temperature of approximately1200℃ or above. Such a high-fringe temperature may have an influence on the pozzolanic reactivity of the aggregate. Therefore, an experimental investigation related to the pozzolanic reactivity of EPA and effects of SF and FA on lightweight aggregate concrete (LWAC) made up of mixtures of pumice aggregate (PA) and EPA was carried out and the results reported.

ASTM Type III, Portland cement (PC), from Boluin, Turkey, was used in this study. SF, FA, PA and EPA were obtained from Antalya Electro Metallurgy Enterprise, Afsin Thermal Power Plant, Kocapınar region in Van-Ercis, and ETI Bank Perlite Expansion Enterprise in I˙zmir in Turkey, respectively. Sulfonate naphthalene formaldehyde was used as a super-plasticizer, compatible with ASTM C 494 F (high-range water reducer) at a dosage of 1.5 ml/kg of cement. The ASTM D 75, ASTM C 136 and ASTM C 29 were used for sampling, grading, unit weight and fineness modulus of aggregates, respectively. The full details of these properties are given elsewhere. The binder (PC, or PC + SF, or FA) content was 200 kg/m^3 of concrete. Four main groups of mixes of PA and EPA were produced. They were specified as A (100% PA), B (80% PA+ 20% EPA), C (60% PA+ 40%EPA), and D (40% PA+ 60% EPA). For each group, SF–PC, FA–PC mixtures were prepared adding 0%, 10%, 20%, and 30% SF or FA in replacement of PC separately. Hence, 28 different mixes were obtained and cast. The concrete mixes were prepared in a laboratory counter current mixer for a total of 5 min. Hand compaction was used. Precautions were taken to ensure from homogeneity and full compaction. Slump was kept constant at 20 mm ± 5 mm. For each mix, three specimens, 100 mm x 200 mm cylinders, were prepared and cured in lime-saturated water at 20° ± 3℃ until the 6th and 27th days, and then tested for compressive strength in accordance with ASTM C 192.

While FA increased the workability of mixtures, SF decreased. SF and FA decreased the unit weight of samples. Unit weights also decreased with increasing EPA in the mixtures. The unit weights changed between 735 and 1154 kg/m^3. Using EPA replacement of PA at 20%, 40%, 60% allowed us to increase 7-day compressive strengths up to 52%, 85%, 55%, and 28-day compressive strengths up to 80%, 84%, 108%, respectively. EPA increased the 28-day compressive strength up to 108% at 60% EPA replacement of PA,

while it increased the 7-day compressive strength up to 85% at 40% EPA replacement. The effect of EPA increased with increasing curing period. SF decreased the 7-day compressive strength of all groups except Group A, and up to 20% SF replacement of PC. With increasing EPA in the mixtures, the reduction value increased dramatically, and at the maximum EPA ratio, the reduction value was 63% at 7 days. SF increased 28-day compressive strengths of all groups for 10% SF a little, except in Group A. SF is more effective in Group A and increased the 28-day compressive strength at all levels of SF, especially at 20% SF. The maximum increment was 69% for Group A. With increasing EPA, the effect of SF decreased, and with increasing curing time, the effect of SF increased. FA induced a reduction of 7- and 28-day compressive strengths of all groups at all levels of FA replacement of PC except in Group A and 10% FA replacement of PC. Reductions due to FA at 7 days were less than those of SF for mixtures with EPA. Reductions due to FA also decreased with increasing EPA and curing time.

From Topcu and Isıkdag [11], perlite contains 70%–75% silicon dioxide and 12%–16% alumina. Other components are sodium oxide, potassium oxide, ferroxide, manganese oxide, titan oxide and sulfide. The physical properties of EPA are given in Table 9. The unit weight of EPA depends on gradation and expansion. The heat conductivity of perlite with the unit weight of 90 kg/m^3 is 0.04 W/mK at 24°C according to Turkish Standard (TS 3681). In experiments, CEM I 42.5R and CEM II 32.5R produced by ESC¸ IM cement factory was used (TS EN 197-1). Sand and crushed stones were used as aggregate in concrete production. The gradations of aggregates were prepared considering the reference curves (TS 707). The unit weight and specific gravity of aggregates were determined according to Turkish Standards (TS 706 EN 12620). In concrete production network, water was used according to Turkish Standards (TS 1247).

In initial experiments, the effect of cement types were investigated according to 30% EPA ratio. EPA was used instead of fine aggregate (sand) by volumetric batching considering volumetric expansion of perlite after wetted. In laboratory, standard cylindrical (Φ150 mm × 300 mm) and cubic (150 mm × 150 mm × 150 mm) concrete specimens were produced with the cements of CEM I 42.5R and CEM II 32.5R at the dosages of 300, 350 and 400, to determine mechanical and physical properties of concrete containing EPA by conducting fresh and hardened concrete tests on the specimens. In secondary experiments, CEM I 42.5R was used with the dosages of 300, 350, 400, and EPA was used with the replacement ratios of 0%, 15%, 30%, 45% and 60% to determine the effects of EPA on compressive and splitting tensile strengths. The water/cement ratio was determined as 0.5 in the mixtures. The specific weights of sand and crushed stone were 2600 and 2700 kg/m^3, respectively, and the maximum aggregate size was 31.5 mm in concrete mixtures. During production process, the fresh concrete was mixed with a mixer, and specimens were vibrated on vibration table. The workability of concrete mixtures was also determined with slump tests. The concrete specimens were cured in lime saturated water at 23° ± 1°C for 28 days, afterwards destructive and non-destructive tests were conducted on specimens (TS EN 12350, 12390). The dynamic elasticity modulus of specimens was calculated with the formula:

$$E_d\,(10^{-6}) = \frac{V^2 n(1+\mu)(1-2\mu)}{1-\mu} \text{.....[11]}$$

where μ is the Poisson, n is the unit weight (kg/m^3) and V is the pulse velocity (m/s).

Table 9. *Physical properties of expanded perlite [11].*

Color	White
Melting point	1300 °C
Specific heat	0.20 kcal/kg °C
Unit weight	2.2–2.4 g/cm^3
Rough density	30–190 kg/m^3
Heat conductivity	0.034–0.040 kcal/m h °C
Sound insulating	18 db (125 Hz)

The concrete specimens were produced with CEM I 42.5R at the dosages of 300, 350 and 400 considering 0%, 15%, 30%, 45% and 60% replacement ratios to determine the effects of EPA on compressive and splitting tensile strengths. The minimum compressive and splitting–tensile strengths were 15 and 1.5 MPa at the dosages of 300, and the maximum values of these strengths were 37and 3.5 MPa at the dosages of 400, respectively. According to the results, the optimum strengths for lightweight concrete were obtained between 15% and 30% ratios at the dosage of 350 and 400. Furthermore, the results have shown that higher replacement of EPA (60%) negatively affects both compressive and splitting strengths of concrete specimens, but positively affects the lightweight property. According to results, concrete quality between C20 and C40 can be obtained with improving cement quality, dosage or replacement ratio of EPA. It was proved that, the more use of EPA ensures the less strength and better lightweight property. Furthermore, the minimum unit weight for lightweight concrete considering cement types was obtained with the CEMII 32.5R cement at the dosage of 300 with the replacement ratio of 30%; however, the optimum strengths for lightweight concrete were obtained between 15% and 30% ratios at the dosage of 350 and 400 with the CEM I 42.5R. In experiments, it was observed that the compressive strength, splitting–tensile strength and the dynamic elasticity modulus increased with the increase in dosage. However, workability was inconsiderably affected by the cement-type sand dosages. According to experimental results, flow table and slump values decreased as the dosage, cement quality and Vee-Be time increased. Furthermore, the unit weights of concretes increased in parallel with the increase in dosage and cement quality. According to mechanical property of concrete, it was proved that EPA can be used as fine aggregate in concrete with appropriate replacement ratios along with the lightweight property.

OTHER EXPERIMENTAL TEST ON PERLITE:

From Kramar and Bindiganavile [3], plain, unreinforced mixes were cast at four densities to examine a range of lightweight mortars between 1000 and 2000 kg/m^3. The heaviest was effectively a cement paste that served as the reference, containing only Portland cement and a water-to-cement ratio of 0.4. Type GU Portland cement as obtained from local suppliers was used in each mix. The remaining three lower densities were cast with increasing amounts of EP. The EP was sourced from a volcanic glass heated to 870°C, resulting in a lightweight material possessing a high specific surface area. It had a bulk density of 64 kg/m^3 with a maximum particle size of 1.68 mm. The microstructure is characterized by open pores (small channels that form a thick network) and closed pores

(isolated cells and holes). The simultaneous presence of these morphological features gives the mineral an extremely high transpiring power, due to the open pores, and at the same time, some crushing resistance in comparison with other lightweight fillers such as expanded polystyrene, due to the closed pores. The former has led to its use in thermal insulation, while the latter has been utilized in structural lightweight concrete. In the present study, the addition of EP lightweight aggregate was defined by a volumetric ratio of EP with respect to Portland cement (PC), so that together with the reference mix, four mixes with volumetric ratios of 0, 0.8, 4 and 8 were produced. In order to be consistent with the water-to-cement ratio, a mini-slump cone was utilized to conduct a slump test. The mixes were prepared to achieve a slump spread between 130 and 190 mm. Since the EP beads absorb a significant amount of the water added to the mix, an increase in the perlite content was compensated by a corresponding increase in the mix water. Accordingly, the water-to-cement ratio was 0.4 for the reference mix, and also for those containing volume ratio of EP-to-PC equal to 0.8 and 4. For the lightest mix with a volume ratio of EP-to-PC of 8, the water-to-cement ratio was raised to 0.8. Polymeric microfibers were chosen as discrete reinforcement due to their low modulus and high aspect ratio. The mixes in this investigation contained no coarse aggregate and as is well known, lightweight cementitious composites tend to be more brittle. Therefore, an additional three mixes were reinforced with polypropylene micro-fibers that were 20 mm long with a maximum Denier count of 3 (in g/9000 m) and an elastic modulus of 3450 MPa. In order to retain adequate workability, a relatively low fiber volume fraction of 0.1% was considered. As there was no significant change in density for EP/PC equal to 0.8, only the reference cement paste and the two lightest mixes were reinforced with fibers.

In plain mortars under compression, the addition of EP leads to a density scale effect for strength and elastic modulus under compression. Both strength and elastic modulus scale as the cube of the relative density and defined as the ratio of the density of the mortar to that of Portland cement paste. In plain mortars subjected to bending under quasi-static loads, both strength and fracture toughness scale linearly with the relative density of the mix. However, under impact loading, the flexural strength and Mode-I fracture toughness are more sensitive to the density of the mixture. The fracture toughness of fiber-reinforced cementitious mortars is more sensitive to the relative density than that of plain unreinforced mixes. The difference in sensitivity between plain and fiber-reinforced mortars is more pronounced during their impact response. In lightweight cement-based mortars, the stress rate experienced under identical velocity of impact strongly depends upon the density of the composite. For the range of mixes examined, a two-fold increase in weight resulted in a 20-fold increase in the stress rate experienced. Reinforcing lightweight mortars that contain EP with polymer micro-fibers affects the stress rate sensitivity of their flexural strength and Mode-I fracture toughness. While the flexural strength becomes more rate sensitive, the latter was seen to be less sensitive to stress rate in the presence of fibers.

From Alazhari et al. [7], *Bacillus pseudofirmus* DSM 8715 (German collection of micro-organisms and cell cultures (DSMZ)) was used in this study. Living cells were routinely cultured on buffered lysogeny broth (LB) which contained 100 ml/l sodium sesquicarbonate to achieve pH 9.5. Spores were prepared in a sporulation media and incubated at 30°C on an orbital shaker for 72 h. Spores were harvested by centrifugation at 10,000 rpm for 15 min. Spore formation was confirmed

by phase contrast microscopy. The spore pellet was washed three times with a chilled 10 mM Tris HCl buffer, pH 9.5. The spore pellet was then freeze-dried to obtain a spore powder and stored in a desiccator prior to use. Three growth media were investigated. GM1 consisted of a multi-component media based on initial microbiological studies and was selected to maximize as much as possible the germination of bacterial spores, growth of bacterial cells, precipitation of calcite and sporulation of bacteria. GM2 consisted of just three ingredients: calcium acetate (as the precursor), yeast extract and dextrose as the nutrients. The ingredients were used in proportions similar to those in research elsewhere. GM3 consisted of the same three constituents as GM2 but in much higher proportions, such that the solution was almost saturated with these components. When used in microbiological experiments, the growth media were buffered with tri-sodium citrate, sodium bicarbonate and sodium carbonate (in the case of GM1) to provide an alkaline environment suitable for growth of *B. pseudofirmus*. EP is a lightweight, amorphous, mineral aggregate commonly used in horticultural applications in plant growth media. The particle size distribution of the EP as determined in accordance with BS EN 933-1 and it conformed to a 0/4-mm aggregate according to BS EN 12620. The EP had a water absorption capacity of 146%, an apparent density of 292 kg/m^3 and a loose dry bulk density of 122 kg/m^3.

A series of mortar mixes was produced using Portland FA cement (CEM II/B-V), standard sand (BS EN 196-1) and tap water. The sand-to-cement ratio in the control mortar (MC) was 3.0 and the water-to-cement ratio was 0.5 by mass. Combinations of CPN and CPS were added to the concrete as self-healing agents as a combined replacement of 20% by volume of sand. In mortar M100, the sand was replaced with CPN only. In M90 to M50, a combination of CPN and CPS was added in ratios of 9:1, 4:1, 7:3, 3:2 and 1:1, respectively. The mix number reflects the percentage of CPN to total coated EP (CPS + CPN) by volume. Mixing was carried out in accordance with BS EN 196-1, with the coated perlite added at the same time as the sand. The specimens produced were disks with a diameter of 100 mm and thickness of 10 mm. After casting, the molds were placed in a controlled environment room (20℃, 40% RH) for 24 h. All specimens were demolded at 24 h and stored in water at 20℃ until an age of 28 days.

The self-healing capability of a dual system consisting of bacterial spores and nutrients encapsulated separately in EP was demonstrated based on microscopy and initial surface absorption of water. It was shown that crack healing could be achieved when coated EP was used as a 20% replacement of aggregate, provided a suitable ratio of spores to calcium acetate was achieved. For the particular method and conditions used in this paper, this ratio appears to be in the order of 8×10^9 spores per gram of calcium acetate. The results showed for the first time that self-healing is not simply a requirement of having sufficient healing compounds (e.g. calcium acetate) but that a minimal number of bacterial spores are also required to ensure that sufficient cells take part in the healing process. Based on microbiological experiments, it was shown that more rapid and efficient precipitation of calcium carbonate occurs in the presence of other nutrients rather than in a growth media comprising just yeast extract. In this research, healing was achieved in a moist and humid environment which required up to 165 days for healing to occur. It is likely that faster healing can occur in a wet/dry environment; however, the actual environments and exposure conditions that

real structures are exposed to are needed to be considered.

From Turkmen and Kantarcı [12], ASTM Type I PC, SP, SF and EPA were used. SP based on chains of modified poly-carboxylic ether was used as an SP, compatible with ASTM C 494 F at a dosage of 2% of cement. Coarse aggregate consisted of crushed basalt. Specific gravity, maximum size and the absorption of this aggregate were 2.64, 16 mm and 2%, respectively. Sand was used as fine aggregate having specific gravity and absorption of 2.31% and 4%, respectively. The binder (PC+SF) content was 450 kg/m^3 of concrete. Four main groups of mixes of NA and EPA were produced. They were specified as EPA0 (100% NA), EPA 5 (95% NA + 5% EPA), EPA 10 (90% NA + 10%EPA) and EPA15 (85% NA + 15% EPA). For all groups, PC–SF mixtures were prepared adding 10% SF in replacement of PC. The counter mixes were prepared in a laboratory counter-current mixer for a total of 5 min. Water/cement + mineral (w/cm) ratio were kept constant at 0.35. Five types of curing conditions were chosen to study the effect of curing environment on the performance of EPA concrete and control concrete. Concrete specimens were stored in these different curing conditions until tested.

The compressive strength of specimens was obtained in the five different curing conditions at the 28th day. For each mix, three specimens, 100 mm × 200 mm cylinders and 70 mm × 70 mm × 70 mm cubes, were prepared. After 1 day of curing, the specimens were stored at constant temperature in lime-saturated water (CC1), dry in air (CC2), wetted three times a day for14 days, and then cured in air (CC3), under wet sack for 14 days and then cured in air (CC4), and 100% constant relative humidity (CC5) until measuring compressive strength on the 28th day. The compressive strength values were in the range of 53.9–38.3 MPa: the lowest value belongs to EPA15 cured in CC4 for 28 days and the highest value to EPA0 cured in CC1. In general, EPA reduced the compressive strength of concrete at the 28th day. Reductions for compressive strength at 28-day curing period were 1%, 3% and 7% for 5%, 10% and 15% EPA replacement of NA in CC1 conditions, respectively. It can be noted that the compressive strength of EPA concrete was lower than those of NA concrete except for EPA5, EPA10 and EPA15 in CC2 conditions. It may be due to the filler effect of EPA on the SCC, and to the lightweight aggregate manufactured at a firing temperature of approximately1200°C or above. Such a high temperature may have an influence on the pozzolanic reactivity of the aggregate–cement paste interface. This may be due to some reinforcement of the outer shell of the aggregate and bond enhancement due to the continuity in the CHS outside and inside aggregate.

It can be seen from the results that all concrete samples are SCC. The compressive strength of EPA concrete was lower than those of NA concrete except for EPA5, EPA10 and EPA15, in CC2 conditions. The capillarity coefficient of concrete for CC1 curing conditions decreased more than other conditions for 28, 56, 90, 120- and 150-days curing periods and changing of the capillarity coefficient values depended on the curing time, curing conditions, and the percent of EPA. The apparent porosity for CC2 curing condition increased more than the other conditions with increasing EPA ratio for 28-day curing period.

From Zukowski and Haese [15], the influence of EPA, SF, pumice and FA on physical properties of lightweight concrete were investigated by Demirboga and Gul. Measurements indicated that when pumice

aggregate is replaced with EPA, the heat conductivity of concrete was reduced by over 40%. The lowest value was equal to approximately 0.15 W/mK for the complete replacement. The samples that contained pumice aggregate and Portland cement had the highest value of thermal conductivity which is equal to 0.32 W/mK. EP is often used in lightweight concrete constructions. Ray et al. preliminarily investigated the utilization of perlite fine waste as an alternative to supplementary cementitious materials. Mortar samples containing fine perlite, FA and SF were experimentally examined by using three methods: thermogravimetry, differential thermal analysis and compressive strength determinations along with XRD. The author concluded that the samples with fine perlite gave superior, unconfined compressive strength to the samples containing FA, and were comparable to Portland cement samples. Finite volume method was used to find the optimum holes arrangement for the hollow clay bricks. Estimates indicated that the best configuration composed of eight holes in length, four holes in width and one hole in height for 29 cm × 14 cm × 9 cm building block. The equivalent thermal conductivity of this sample was equal to 0.4 W/mK. The air cavities in the above works had the same shape and were arranged in parallel. The voids in the hollow brick, investigated by the author of this article, are arranged differently in order to reduce the effect of thermal bridges and maximize the insulation's effectiveness. A calibrated hot-box unit was applied to determine static and dynamic properties of building components by Sala et al. and by Wakili and Tanner. Determination of *U*-value for a wall made of porous clay perforated bricks was carried out with very high precision. The authors of this investigation even paid special attention to the penetration of mortar into the voids of the brick.

The experimental investigations and numerical analysis were designed and conducted to find the basic data required for an energy simulation program. It is suggested to use the following equivalent parameters of the new hollow brick in calculations: heat capacity equal to 855.1 J/kg K, heat conductivity equal to 0.09W/mK and unit weight equal to 653.15 kg/m^3. It is important to underline that modern hollow bricks filled with perlite characterizes high thermal resistance and can be applied without any additional insulation layer. In this case, the total *U*-value of a wall is lower than 0.29 W/m^{2}K. As it turned out, the perlite insulation has often been damaged on the construction site most likely during the manual handling of the bricks. This incorrect practice of the brick layers can increase the penetration of mortar into the spaces and, as a consequence, thermal energy consumption will increase. Thus, further more investigations of thermal performance of complete external walls and on the estimation of real energy consumption in buildings have to be carried out for better performance.

CONCLUSION

From the above research works, the following results have been derived:

- The thermal conductivity of the mixture containing 40% EP is 12% lower compared to that of the reference mixture, but it is of 65% with 80% perlite.
- The difference between the sprayed and cast mixes may be attributed to a transverse isotropy and superior consolidation in the former; an explanation that is consistent with research on self-compacted concrete, where in a power-law with an exponent of 1.04 was obtained.
- Reduction in *k*-value decreases the thermal gradient developed in the rigid pavement. This helps in preventing

premature cracking of pavement on account of temperature variation.

- It is found that the qualified thermal performance has showed significant application potential for CPCMW incorporated with building envelope to passively adjust the indoor air temperature and increase the thermal mass of building, especially for lightweight building.
- The combined effect of the porous nature of perlite and the increased cellular CSH gel formation with SF addition results in lower thermal conductivity values in FA–lime–gypsum mixture. Steam curing and super--plasticizer addition were found to be useful for the strength increment of the FA–lime–gypsum mixture.
- The optimum replacement percentage of sand by perlite is 10%. The compressive, split tensile and flexural strength were reduced if the replacement percentage of perlite is increased.
- Based on microbiological experiments, it was seen that more rapid and efficient precipitation of calcium carbonate occurs in the presence of other nutrients rather than in a growth media comprising just yeast extract. In this research, healing was achieved in a moist and humid environment which was required up to 165 days for healing to occur.
- Modern hollow bricks filled with perlite characterize high thermal resistance and can be applied without any additional insulation layer. In this case, the total *U*-value of a wall is lower than 0.29 W/m^2K. As it turned out, the perlite insulation has often been damaged on the construction site most likely during the manual handling of the bricks.

REFERENCES

[1] Demir I, Baspinar MS. Effects of silica fume & expanded perlite addition on the technical properties of the flyash-lime-gypsum mixture. *Constr Build Mater*. 2007; 22(6): 1299–1304p.

[2] Sengula O, Azizi S, Karaosmanoglub F, Tasdemir MA. Effects of expanded perlite on mechanical & thermal conductivity of lightweight concrete. *Energy Build*. 2010; 43(1–3): 671–676p.

[3] Kramar D, Bindiganavile V. Impact response of lightweight mortars containing expanded perlite. *Cem Concr Compos*. 2012; 37(3): 205–214p.

[4] Liu WV, Apel DB, Bindiganavile VS. Thermal properties of lightweight dry-mix shotcrete containing expanded perlite aggregate. *Cem Concr Compos*. 2014; 53: 44–51p.

[5] Gandage AS, Vinayaka Rao VR. Effect of perlite on thermal conductivity of self-compacting concrete. *Soc Behav Sci*. 2013; 104: 188–197p.

[6] Bhuvaneshwari K, Dhanalakshmi G, Kaleeswari G. Experimental study on lightweight concrete using perlite. *Int Res J Eng Technol*. 2017; 04(04): 2451–2455p.

[7] Alazhari M, Sharma T, Heath A, Cooper R, Paine K. Application of expanded perlite encapsulated bacteria and growth media for self-healing concrete. *Constr Build Mater*. 2017; 160: 610–619p.

[8] Isıkdag B. Characterization of lightweight ferrocement panels containing expanded perlite-based mortar. *Constr Build Mater*. 2015; 81: 15–23p.

[9] Fodil D, Mohamed M. Compressive strength and corrosion evaluation of concretes containing pozzolana and perlite immersed in aggressive environments. *Constr Build Mater*. 2018; 179: 25–34p.

[10] Kong X, Yao C. Development and thermal performance of an expanded perlite-based phase change material wallboard for passive cooling in building. *Energy Build*. 2017; 152: 547–557p.

[11] Topcu IB, Isıkdag B. Effect of expanded perlite aggregate on the properties of lightweight concrete. *J Mater Proc Technol*. 2007; 204: 34–38p.

[12] Turkmen I, Kantarcı A. Effects of expanded perlite aggregate and different curing conditions on the physical and mechanical properties of self-compacting concrete. *Build Environ.* 2006; 42: 2378–2383p.

[13] Demirbog R, Orung I, Gul R. Effects of expanded perlite aggregate and mineral admixtures on the compressive strength of low-density concretes. *Cem Concr Res*. 2008; 31: 1627–1632p.

[14] Karakoç MB, Demirboğa R, Türkmen İ, Can İ. Effect of expanded perlite aggregate on cyclic thermal loading of HSC and artificial neural network modelling. *Sci Iranica A*. 2011; 19(1): 41–50p.

[15] Zukowski M, Haese G. Experimental and numerical investigation of a hollow brick filled with perlite insulation. *Energy Build*. 2010; 42: 1402–1408p.

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