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PRACTICE-ORIENTED PAPER

An innovative technique for internal curing of concrete with brick aggregate, nanoparticles of Al_2O_3 and rubber latex

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Abstract

Internal curing of high strength concrete by pre-saturated lightweight aggregate has been proved as an effective curing method in reducing the self-desiccation and autogenous shrinkage of concrete. In previous research, internal curing has been done by continuously supplying water to the fresh cementitious mixture using reservoirs via prewetted lightweight aggregates. These lightweight aggregates compensate for the loss of moisture due to self-desiccation or evaporation of water from the concrete surface. But this additional supply of water from lightweight aggregates is not sufficient for high humid areas or tropical reasons, where the evaporation of water is more. In that condition, a continuous water supply is required to fresh concrete by external means. In this study, a new technique has been applied on developing an internal curing approach for high strength concrete immediately to after casting and new materials (natural rubber latex and brick aggregate) have been introduced to accelerate the internal curing process at an early age and sealed the voids of concrete at a later age. In this research, the loss of water during evaporation has been compensated by supplying of water through cotton threads externally. This externally supplied water is absorbed by brick aggregates and stored inside them. That means in previous research limited water was supplied through lightweight aggregate which was not sufficient for construction at high humid areas. But in the present research, the water demand has been fulfilled for internal curing through external supplying; when concrete demands at whatever amount.

Keywords Brick aggregate · Internal curing · Natural rubber latex · Nanoparticles · Porosity

Introduction

The curing of concrete plays an important role in maintaining the required moisture content and temperature immediately after placing and finishing to develop desired properties of the concrete structure [1]. As the fresh concrete does not possess enough stiffness to prevent surface erosion, at that moment the curing process should be started [2]. The proper curing of concrete may increase strength, durability, permeability, volume stability, abrasion resistance, etc. [3]. The concrete with a low water–cement ratio (less than 0.36) may require special curing [4]. Because the internal relative humidity starts to decrease when the hydration process begins if no water is provided externally. When the hydration process stops, the cement paste may self-desiccate. At the first seven days of curing, if the internal relative humidity of concrete reduces 80%, then the strength and durability properties of concrete hamper significantly [5]. By resuming the moist curing, the development of strength can be reactivated. It may be possible in the laboratory not in the field. In this condition wet curing or fogging is essential for accelerating the hydration process. Also, this method reduces the surface cracking of concrete due to plastic shrinkage for low water–cement ratio concrete. Hence moist curing process should be provided to

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cement mortar or concrete continuously at the beginning when the placing and finishing process completes and should be continued until it has gained sufficient strength [6]. It has been found that the hydration process of concrete requires a certain temperature. The hydration process becomes very slow at low temperatures particularly below 10 °C, which is unfavorable for gaining early strength [7]. Also, the hydration process hampers at high temperatures due to insufficient water after evaporation [8]. Hence an artificial continuous curing system should be provided to maintain the temperature and moisture at an early stage for the favorable condition of hydration. Two types of strategies can be adopted for artificial continuous curing. The first one is the provision of an internal reservoir of water by using lightweight aggregate and the second one is using super absorbent polymers as an admixture in concrete [9].

Portland Pozzolana Cement (PPC) is using in the construction of building and infrastructure because of eco-friendly and its excellent durability [10]. The Portland Pozzolana Cement contains 25–35% fly ash. Hence the early age strength development of concrete using Portland Pozzolana Cement is sometimes slower than the Ordinary Portland Cement because of the slow pozzolanic reaction of fly ash [11]. It has been found that the higher percentage of replacement of cement with fly ash has provided better strength at a later age [12]. From the outcomes resultant from Taguchi and Multi-Regression Analysis, it was found that the fly ash content in Portland Pozzolana Cement is the most leading control factor in both flexural and compressive strength [13]. The higher percentage of fly ash-based Portland Pozzolana Cement concrete requires a long period of curing with proper curing conditions [14]. This increases the construction cost. Hence internal curing can be selected as an alternate method to minimize the curing cost of concrete. The improvement in strength and durability, as well as reduction of early age cracking, can also be possible for high-performance concrete with a low water–cement ratio by internal curing [15].

For reducing the shrinkage as well as promoting the hydration process, prewetted lightweight aggregate has been introduced in a high-volume fly ash concrete mix with a low water–cement ratio. The coarse aggregate has been replaced with clay roof tiles by 20–40% in fly ash concrete for reducing autogenous shrinkage and increasing the early and later age strength [16]. It has been found that the early age shrinkage reduced half when the brick aggregate was used as coarse aggregate in geopolymer concrete [17]. Cachim (2009) has stated that using pre-saturated brick aggregate in concrete provides 8–23% excess water than that specified by the water/cement ratio, which can be used for hydration of cement at a later age without contributing the porosity [18]. Manzur et al. (2019) had stated that under adverse curing conditions, brunt clay brick chips of 9.5 mm size can replace stone chips of the same size up to 20% for producing internally cured concrete [19]. Mohammed et al. (2014) recommended that stone aggregate can be replaced by recycled brick aggregate up to 50% without reduction of compressive strength [20]. Recycled brick aggregate concrete was showing better performance w.r.t abrasion and absorption capacity.

For encouraging sustainable construction practice, people are using natural rubber latex in concrete for modification for cement composite. Using rubber latex in plain concrete, the ITZ layer had been improved and the porous concrete had changed into impermeable concrete with denser microstructure by forming a lining of latex film across pores, voids and microcracks [21]. Also, natural rubber latex had been used in geopolymer concrete as an admixture which had improved the workability and rheology property and reduced the early age shrinkage of concrete [17]. The addition of rubber latex decreases the volumetric shrinkage of concrete. Rubber latex forms a film around the water particle and does not allow to evaporate the water [22]. The addition of rubber latex in concrete decreases the early age shrinkage process due to evaporation as well as reduces the development of shrinkage cracks on the concrete surface significantly. Thus, rubber latex can be used in concrete as an organic shrinkage reducing admixture. Using rubber latex in mortar up to 30%, it had found that the setting time of mortar decreased as the percentage of rubber latex dose had increased. Also, it had recommended that both cement and water should not be replaced more than 10% with GGBS and water simultaneously to achieve desired compressive strength [23]. Subash et al. (2020) used the natural rubber latex as a partial replacement of water up to 6% and found a better result about compression, split tensile, flexure and microstructural properties concrete [24]. Different experimental findings regarding the influence of rubber latex modified concrete in sulfated as well as acidic environments have also been reported. It was found that the strength of rubber latex mixed concrete gained the highest percentage as 33.7% at H_2SO_4 environment and as 18.9% at Na_2SO_4 environment when 1.5% and 5% water was replaced significantly with rubber latex [25].

Nowadays nanoparticles of several compounds such as Al_2O_3, TiO_2, Fe_2O_3, ZnO, SiO_2, ZrO_2 as well as carbon nanotubes are utilizing in concrete to improve the mechanical, physical, thermal and microstructure properties. These nanoparticles have been used in concrete as a cement replacement material for improving the compressive strength [26]. It helps in the rapid formation of calcium hydrated gel by reacting with water and other cementitious material, which provides extra strength to concrete. The compressive strength of concrete had increased 30% when 0.25% of Al_2O_3 nanofibers of cement weight were added to concrete [27]. When 5% of nanoparticles of Al_2O_3 were added to cement, it was found that chloride binding ability increased by 37% [28]. But when 2% of Al_2O_3 nanoparticles were used in cement paste the chloride binding property increased by 35% [29]. Better strength and durability characteristics were enhanced by triple blending of 3% Al_2O_3 nanoparticles, 10% textile sludge and 77% cement [30]. When 5% of Al_2O_3 nanoparticles were used in concrete the microstructure had highly improved and 50% of voids were filled by extra formed C–S–H gel [31]. Replacing of cement with nanosilica up to 1% and ZnO up to 0.5% combinedly in concrete helped to increase the strength and durability of concrete by reducing the amount of $Ca(OH)_2$ and increasing the amount of C–S–H gel in tricalcium silicate [32].

In the northeast India region such as Tripura, brick aggregates are traditionally used as a coarse aggregate, due to the unavailability of natural stones [33]. A lot of brick kilns have been established inside the Tripura state and people are earning their bread and butter by working in these factories. In the present research, these bricks were broken into small pieces and used as aggregate in concrete. When brickbats were using as aggregate in concrete, they acted as an internal curing agent and developed better-hydrated concrete, with lower shrinkage with improved interface transition zone [34]. Also, a large number of rubber plants are seen in the forest of Tripura. The state government also encourages to people for cultivation of rubber. In the northeast region of India, Tripura state produces about 58% of rubber. Since rubber latex was easily available in the Tripura market, it was decided that to use it in concrete.

Research significance

Several types of research have been conducted on the effects of the internal curing of concrete by using various internal curing agents. It also found that due to using internal curing agents in concrete, there is a tremendous increase in early age strength of conventional concrete with enhancing the desired durability and reducing the autogenous shrinkage [35]. In general, the high strength concrete possesses a low water–cement ratio and the durability of such type of concrete is easily affected by early age shrinkage due to rapid evaporation of water. Many researchers have focused the effect of internal curing on various properties of high-volume fly ash concrete such as compressive strength up to one year, autogenous shrinkage up to 180 days, several durability properties [36]. In the present research, three internal curing agents such as natural rubber latex (replaced to water up to 2% by weight), brick aggregate (100% replacement with stone aggregate) and nanoparticles (replaced to cement up to 4% by weight) have been used in concrete having a water–cement ratio of 0.3. In this research crushed brick of size 20 mm has been used as coarse aggregate, rubber latex has partially replaced to water up to 2% and cement has been partially replaced by nanoparticles of Al_2O_3 up to 4%. Various tests for internal curing have been conducted. It was found that brick aggregates provided an internal water reservoir that supplies water at a regular interval to accelerate the hydration process. Rubber latex created an osmotic pressure to accelerate the capillary action of cotton thread immediately after casting and sealed the macropores and mesopores at the hardening of concrete. Nanoparticles of Al_2O_3 had produced secondary C–S–H gel and filled the capillary micropores of concrete and increased the packing density.

In practice, people are curing the concrete members after removal of formwork, i.e., after 3–4 days of casting. But the hydration process starts when the initial setting time of concrete has finished and evaporation of water starts next to the filling of concrete inside it. In between that period, some amount of the water is already evaporated and the total curing process has been stopped. Hence the voids and shrinkage cracks are formed inside the concrete structure, which reduces the strength and durability. The curing process should be started with concrete after losing the plasticity of cement. A new type of curing arrangement had been adopted to accelerate the internal curing at the plastic stage of concrete for compensating the evaporation of water. The compressive strength, porosity, modulus of elasticity, hydration reactions had been studied to confirm the influence of internal curing on the properties of this concrete. The result of this research will indicate the applicability of brick aggregate, natural rubber latex and nanoalumina particle as an internal curing water tank.

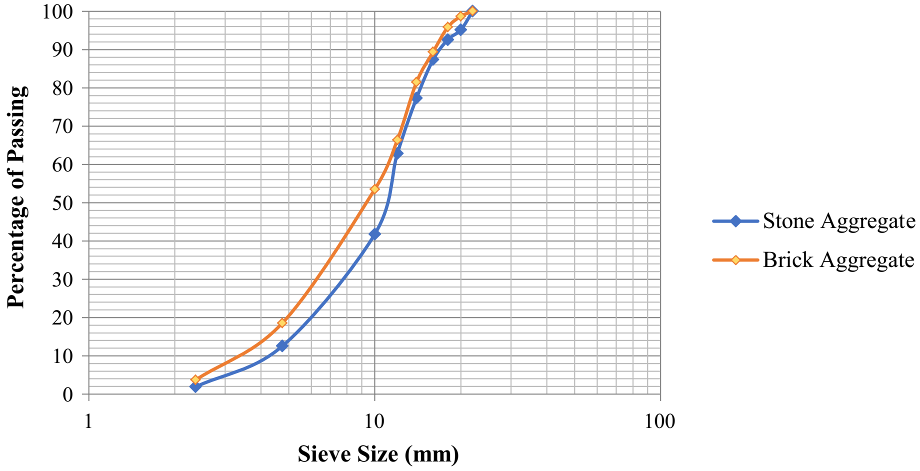
Methodology

In this research Portland Pozzolana Cement was used as binding materials, the saturated brick aggregate was used as coarse aggregate, white color liquid natural rubber latex was replaced with water in fresh concrete up to 2% whereas the nanoparticles of Al_2O_3 were used as partial replacement of cement up to 4%. The physical and chemical properties of materials are given in Table 1. All the laboratory tests have been conducted at ICFAI Tripura and National Institute of Technology Agartala. Here brick aggregate, rubber latex and nanoparticle of aluminum were used as internal curing agents. Seeing the moderate water absorption capacity of brick aggregate, it was used for one of the internal curing agents. The sieve analysis of stone aggregate, brick aggregate and sand are shown in Fig. 1. Since the immersion of brick aggregate in normal tap water was found ineffective [9], they were dipped inside the boiling water for few hours or subjected to absorption under vacuum. Since nanoparticles of aluminum were finer than cement, they were replaced

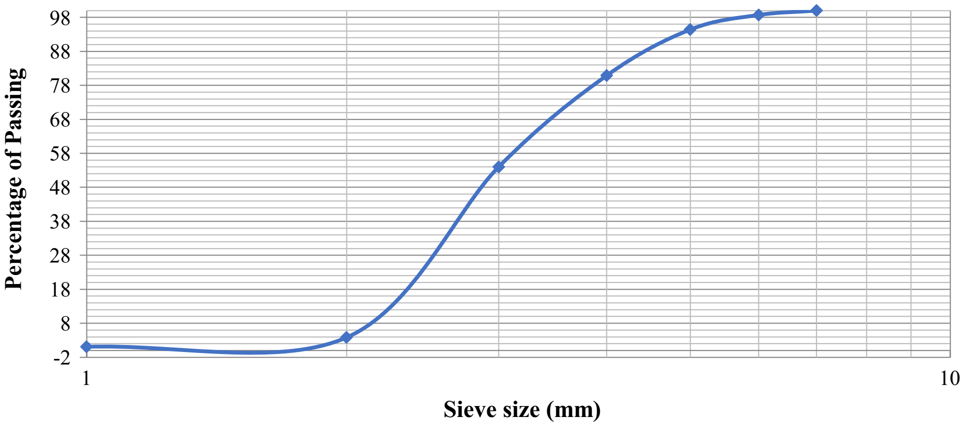
Table 1 Properties of different ingredients used in proposed concrete mix

S.N	Material	Properties
1	Cement	Types of cement: Portland Pozzolana cement, particle size: 60–90 µm. Fineness: 2%, consistency: 35%, initial setting time: 70 min, final setting time: 350 min
2	Sand	Specific gravity: 2.65, grading as zone: Zone-III (according to particle size distribution), specific gravity: 2.61, fineness modulus: 2.67, bulk density (loose): 1643 kg/m^3, bulk density (compacted): 1852 kg/m^3
3	Stone aggregate	Maximum size: 20 mm, specific gravity: 2.73, fineness modulus: 5.9, bulk density: 1600 kg/m^3, voids ratio: 0.45, water absorption: 0.4%, surface index: 0.44, impact value: 14.5%, crushing value: 18%
4	Brick aggregate	Maximum sizes are 20 mm, specific gravity = 1.84, void ratio: 0.48, water absorption: 7% (before using in concrete it is deep inside water for 24 h), crushing value: 21%
5	Al_2O_3 nanoparticles	White colored powder, density: 0.3 g/ml, melting point: 2050 °C, boiling point: 2990 °C,
6	Rubber latex	The natural free-flowing white liquid collected from the rubber tree, specific gravity: 1.04, pH: 8.1, total solid content: 62.48%, dry rubber content: 58.75%, volatile fatty acids: 0.015%

Fig. 1 Gradation curve of coarse aggregate and fine aggregate



(a) **Gradation Curve of Stone Aggregate and Brick Aggregate**



(b) **Gradation Curve of Fine Aggregate**

with cement for increasing the packing density of the concrete mix. The natural rubber latex was found in liquid form while collecting from the rubber tree and its specific gravity was nearer to water. Hence it was decided that it could be replaced with water partially. The rubber latex loses its plasticity within 3–4 h after collection from trees. After one day it makes solid. Thus, rubber latex was collected from the tree before one hour of mixing.

Total ten types of mixes were prepared by varying different percentages of rubber latex and nanoparticles as shown in Table 2. All the mixes are written in the form $M_{x,y}$. The x indicates the percentage of nanoparticles replaced with Portland

Table 2 Concrete mix proportions

Mix	Cement (kg/m^3)	Al_2O_3 nano-particles (kg/m^3)	Sand (kg/m^3)	Stone aggregate (kg/m^3)	Brick aggregate (kg/m^3)	Water (kg/m^3)	Rubber latex (kg/m^3)	Slump Ht (cm)
MT	450	0	753	1182	0	135	0	28
$M_{0\text{-}0}$	450	0	753	0	800	135	0	35
$M_{1\text{-}1}$	445.5	4.5	753	0	800	133.7	1.3	41
$M_{1\text{-}2}$	445.5	4.5	753	0	800	132.3	2.7	46
$M_{2\text{-}1}$	441	9.0	753	0	800	133.7	1.3	44
$M_{2\text{-}2}$	441	9.0	753	0	800	132.3	2.7	50
$M_{3\text{-}1}$	436.5	13.5	753	0	800	133.7	1.3	49
$M_{3\text{-}2}$	436.5	13.5	753	0	800	132.3	2.7	56
$M_{4\text{-}1}$	432	18	753	0	800	133.7	1.3	54
$M_{4\text{-}2}$	432	18	753	0	800	132.3	2.7	63

Pozzolana Cement whereas *y* indicates the percentage of rubber latex replaced with water. A constant water–cement ratio of 0.3 was used for all types of concrete mixtures. It was found that by using the rubber latex up to 2% by replacing the water, the slump height of concrete was increased [17]. Hence, no superplasticizers were used in the present concrete mix. Before the preparation of concrete mix, a new type of arrangement had been prepared for getting a better effect of internal curing. At first 150 mm cubic size of concrete mold was built with plywood. The sidewall of the plywood was made of holes of size 1 mm diameter with spacing 3 mm horizontally and three layers vertically as shown in Fig. 2a. The cotton threads were woven passing through that hole by piercing two opposite wall faces. In this way, three layers of the cotton net had been formed. Care was taken that a sufficient length of cotton threads was extended outside after penetrating the opposite-faced wooden wall for immersing inside the water. All the holes on the sidewalls and edges of mold were sealed by wax

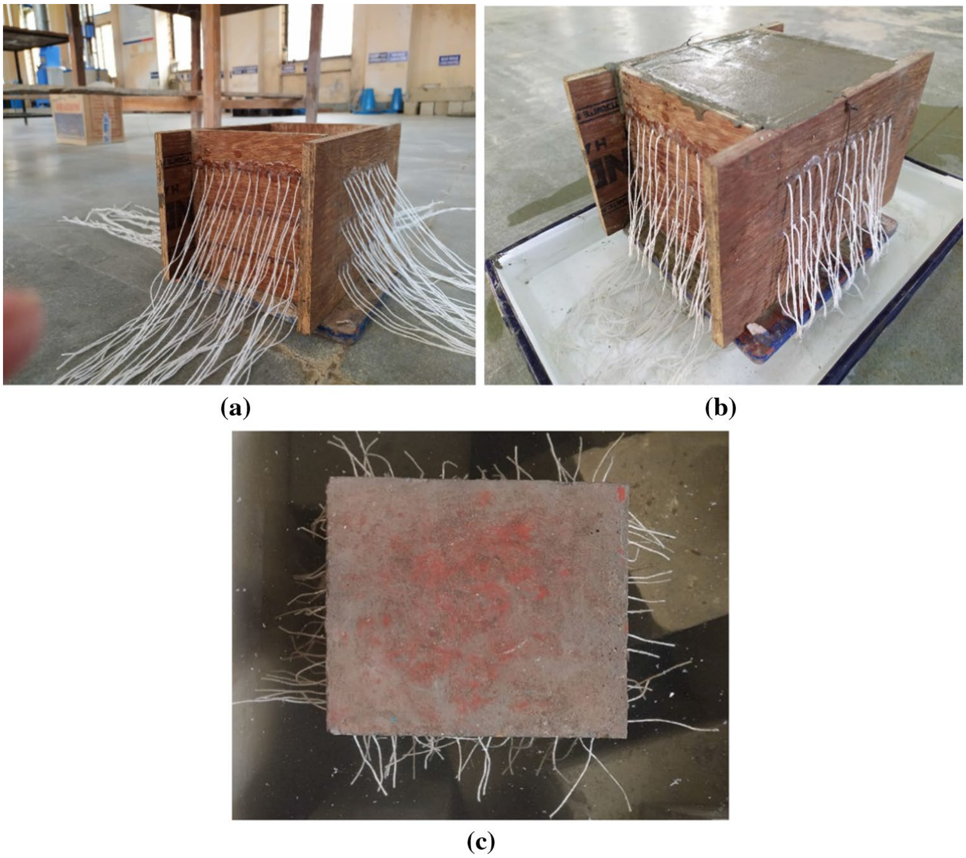

(a) (b) (c)

Fig. 2 A new type arrangement of internal curing **a** threads are woven at all faces of the wooden mold, **b** internal curing at plastic stage of concrete **c** curing of concrete mold after demolding to avoid leakage of concrete. The nine types of concrete mixes were prepared as per the mix design of concrete as shown in Table 2. The prepared concrete was poured inside the new arrangement concrete mold and vibrated by keeping it on the vibrating table. After compaction, the top portion of the concrete cube was finished by striking out the trowel on the surface. After that, the whole mold was kept inside a water vessel by dipping the extended cotton threads inside the water as shown in Fig. 2b. That is why the water was flowing continuously from bowl to concrete inside the mold through capillary action. The care was taken that the bottom of the plywood mold should not touch to water. For this purpose, one wooden plank had kept inside the water vessel and the concrete mold was kept on that plank. Hence the base of the wooden mold would not bulge with the contact of water and the loss of water during evaporation was compensated throughout the hydration process with the help of capillary action. After 24 h the concrete cubes were demolded and cut down the extended threads from all faces and immersed in a curing tank for 28 days as shown in Fig. 2c. This small extended thread will act as dual works. The first one is it will keep moisture inside the concrete throughout the curing by capillary action and the second one is the fined cotton thread will act as fiber and increase the strain-hardening property by providing extra strength to the concrete specimen. This special arrangement of internal curing had provided to all mixes except the traditional concrete.

After 28 days of curing the cube, the specimen was removed from the water tank and kept in a compressive testing machine for the determination of compressive strength. After completion of the compressive strength test, the crushed particle of size range 2.5–5 mm of cube specimen was collected and dipped inside the acetone for Mercury Intrusion Porosimetry (MIP) test. From the MIP test, the pore size distribution was determined over a diameter range of 0.003–300 µm. Also, the crushed particles of the concrete cube were taken for thermal gravimetry analysis (TGA) to know the amount of $Ca(OH)_2$ content in pastes of concrete specimen. Near about 10 g crushed concrete powder samples were added to 250 ml of HCl solution of concentration 0.1 M and mixed for 30 min by magnetic stirrer at 300 rpm. To know the internal packing density of concrete mixes of present research ultrasonic pulse velocity test (UPV) had been conducted on all samples. From that UPV test value, both static and dynamic modulus of elasticity were determined.

Then it was filtered through the filter paper and the residue that remained on the filter paper was heated at 1000 °C through an electric furnace to eliminate free and chemically bound water. The mass percentages of both aggregate and paste were calculated by the following equations.

$$\text{Mass percentage of aggregate} = \frac{\text{Mass of residue after ignition}}{\text{Mass of concrete powder sample}} \text{X } 100 \tag{1}$$

$$\text{Mass percentage of paste} = 100 - \text{Mass percentage of aggregate} \tag{2}$$

The mass of residue retained on filter paper was taken as mass of aggregate in one gm concrete powder. Again 10 gm of concrete powder was heated first at 100 °C at 20 °C per minute and kept for 30 min to remove the free water. Then the temperature was raised about 1000 °C. Mass of loss after dehydration had been calculated. The ignited mass had determined by subtracting of mass of loss of ignition (LOI) from the initial mass of concrete powder. Mass of paste in the concrete after ignition of the concrete powder can be determined by multiplication ignited mass with the mass of paste. The calcium hydroxide content in the paste can be determined by the following equation.

$$\text{Calcium hydroxide content inpaste} = \frac{\text{Mass loss after ignition of 1000 deg centigrade}}{\text{Mass of paste in the concrete after ignition of concrete powder}} \text{X} \frac{74}{18} \text{X100} \tag{3}$$

Results and discussion

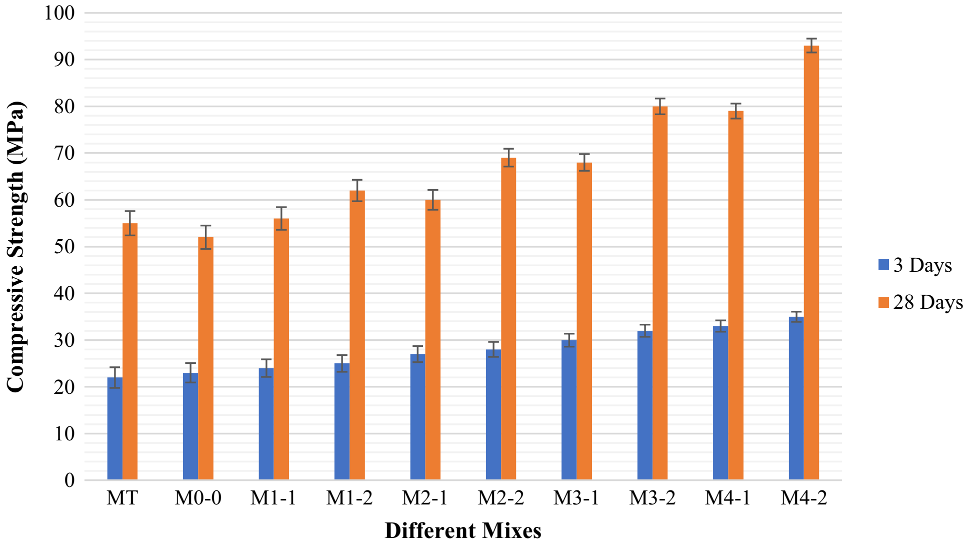
In the present research brick aggregate, natural rubber latex and nanoparticles were used to get better performance in the internal curing process. After mixing of ingredients the slump height was determined. It was found that the slump height increased 25% when brick aggregate was fully replaced with stone aggregate. The absorbed water of saturated brick aggregate on its surface increased its mobility and workability. The simultaneous replacement of cement and water with nanoparticles and rubber latex up to 4% and 2%, respectively, increased the workability about 2.25 times as compared to traditional concrete. When water was replaced by rubber latex, the liquid rubber latex was surrounded with cement particles and formed a similar charge around it. Hence the adjacent two cement particles repelled to each other increased the workability of concrete [17]. By replacing cement with nanoparticles, it increased the packing density by reducing the voids. Hence the surface area of cementitious particles was reduced. Hence less amount of water molecules was utilized to form a film around the cementitious particles. Hence more amount of water was released toward the top surface and the slump height increased. From the above tests, it was found that each internal agent was playing a specific role in the internal curing process. The effects of all internal curing agents on the various test are discussed as follows.

Effect of internal curing agents on compressive strength

The compressive strength of ten concrete mixes at 28 days curing is taken as the average of three samples as shown in Fig. 3. It was found that when the stone aggregate was replaced with brick aggregate the compressive strength of concrete after three days of curing was 4% more than the compressive strength of traditional concrete where stone aggregate was used, but the compressive strength after 28 days of curing was decreased by 6% than traditional stone aggregate concrete. The increment of 3 days compressive strength of brick aggregate concrete indicates that the new arrangement of internal curing had helped to increase the strength of concrete. The cotton threads provided sufficient capillary action to soak the water from the water vessel and kept moist inside the concrete for the first twenty-four hours (inside the concrete mold). The hydration process had already started at the end of the plastic stage. No shrinkage cracks were found on the external surface of the concrete mix. Hence the 3 days compressive strength of brick aggregate concrete was more than the stone aggregate concrete. The lower compressive strength of brick aggregate concrete at 28 days may be a lesser crushing strength value of brick aggregate. The early research had informed that when the coarse aggregate was fully replaced with brick aggregate the compressive strength decreased by 33% [37]. It indicates that using brick aggregate in concrete as an internal curing agent had compensated for the loss of compressive strength. Initially, the saturated brick aggregate absorbed water and stored inside the pores of brick aggregate. That absorbed water was released gradually during the hydration period. It helped to compensate for the evaporation of water at an early age and maintained a constant water–cement ratio throughout the hydration process and formed extra C–S–H gel reacted with fly ash of Portland Pozzolana Cement, which provided better compressive strength. By using of brick aggregate, an effective bonding might be provided between the brick aggregate and cement paste at the ITZ due to increasing of C–S–H gel formation. The Ca/Si ratio of ITZ and microhardness was higher than that of hardened cement paste. The additional water supplied by the saturated brick aggregate had promoted a higher degree of hydration and lead to filling the pores with dense C–S–H gel and increased the strength of cement paste.

Again, it was found that when both cement and water were replaced simultaneously with Al_2O_3 nanoparticles up to 4% and rubber latex up to 2% respectively, the compressive strength for 3 days and 28 days increased gradually. The 28 days compressive strength of brick aggregate concrete replaced 4% of cement with nanoparticles of alumina and 2% of water with rubber latex, was found 40% more than the compressive strength of traditional concrete. The nanoparticles of Al_2O_3 filled the gaps between fly ash and cement particles and increased the packing density of concrete and also consumed portlandite, i.e., $CaOH_2$ [31]. The consumption of portlandite due to pozzolanic reaction with fly ash present in Portland pozzolana cement formed additional C–S–H gel which filled capillaries and reduced the pore structures of concrete. It helped to increase the strength of concrete. Also, the nanoparticles behaved as nuclei for cement paste, which accelerated the hydration reaction [26]. Rubber latex also played an important role to increase the compressive strength by accelerating the internal curing process. Due to the replacement of water with rubber latex by 2% in concrete, it might be decreased the concentration of mix. Hence an osmotic pressure might be developed and

Fig. 3 Effect of internal curing on 3 days and 28 days compressive strength of different concrete mixes



increased the capillary action of cotton threads. As a result, the water moved from the higher potential to the lower potential through capillary action. Hence it was found that the percentage of increment in 3 days compressive strength was more than 28 days compressive strength of each mix as compared to traditional concrete compressive strength. Provision of thread in concrete cube provided early age strength to concrete. Again, the specific gravity of rubber latex is slightly more than the water. Hence it settled inside the voids between the coarse aggregates and fine aggregates. After the lapse of time rubber latex became solid and sealed the pores completely. It helped to increase the compressive strength again. Previously it was seen that the replacement of cement with nanoparticles of Al_2O_3 up to 3% helped to increase the strength of concrete and beyond that, the strength of concrete gradually decreased [31]. But in the present research, the strength of concrete increased even though the replacement of cement with Al_2O_3 nanoparticles was beyond 3%. This was possible due to the presence of 2% of rubber latex. Al_2O_3 nanoparticles helped to form extra C–S–H gel whereas rubber latex sealed the pores of the concrete mix. It is concluded that a higher percentage of cement can be replaced with Al_2O_3 nanoparticles with the presence of 2% rubber latex in concrete.

Effect of internal curing agents on internal packing density and modulus of elasticity of concrete mix

The present study aimed to explore the packing density and internal cracking of concrete mix when cement was partially replaced with nanoparticles of alumina and water was partially replaced with natural rubber latex simultaneously. Ultrasonic pulse velocity (UPV) test was conducted on those cubes as per guidelines of IS 13311 (Part-1):1992 [38]. The ultrasonic pulse velocity tester consists of two transducers and one monitor screen. Transmitting and receiving transducers were touched on two opposite faces of the cubes. Data were generated for all ten mixed concrete cubes at the curing ages of 3 and 28 days and shown in Fig. 4. It was found that when the stone aggregate was completely replaced with brick aggregate UPV value increased 1.2% and 2.4% at 3 and 28 days curing, respectively. It indicates that the new arrangement of internal curing through cotton threads provided sufficient water inside the concrete mix for the hydration process. Due to better hydration more amount of C–S–H gel had formed at an earlier stage and made densify to concrete by reducing the internal pores. Also, brick aggregate released absorbed water at certain intervals and compensate for the losses of water due to evaporation. Also, it reduced both drying and plastic shrinkage, by which the shrinkage cracks on the surface as well as inside the concrete cubes were highly minimized. When the cement was replaced with nanoparticles of Al_2O_3 up to 4% and water was replaced with rubber latex up to 2% simultaneously the UPV value gradually increased. The higher value of UPV had shown that the inner materials of concrete were densely packed and no internal cracks due to shrinkage were developed. The nanoparticles filled the voids between the cement particles and rubber latex filled the voids between the aggregates simultaneously and densified to concretes. The continuous supply of water inside the concrete through thread by this new technique resisted the shrinkage and shrinkage cracks. At the time of mixing the rubber latex filled the voids in liquid form, after 3 days of curing it was in a semisolid state and after 28 days of curing the voids were filled by solid rubber latex. Therefore, higher values of UPV were showing for 28 days curing cubes. Hence, the UPV value for mix $M_{4\text{-}2}$ at 28 days of curing was 9.5% more than the traditional concrete mix (MT).

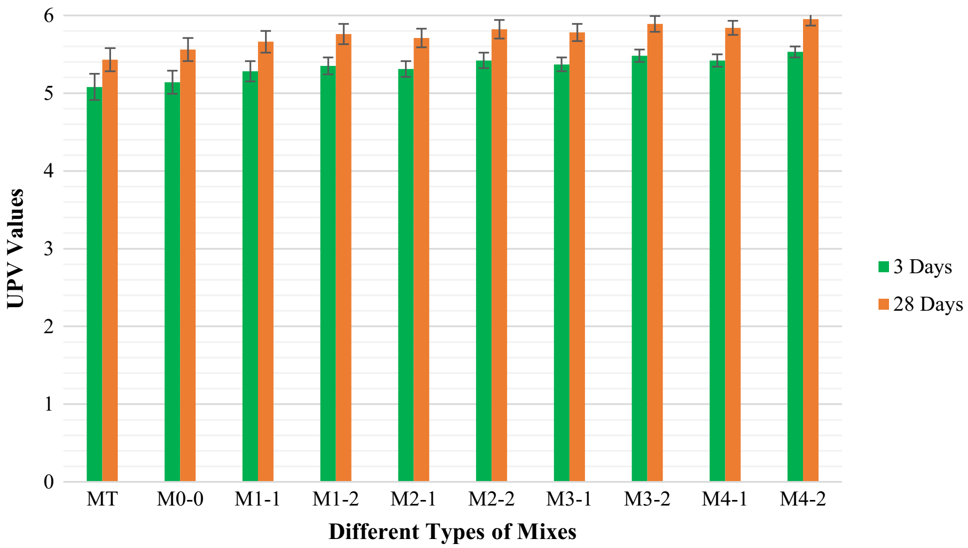


Fig. 4 Ultrasonic pulse velocity values for different mixes

The modulus of elasticity of concrete is a key factor for estimating the deformation of structural elements, as well as a fundamental factor in determining the modular ratio, which is used for the design of structural members subjected to flexure. For designing a structure, the designer requires not only compressive strength but also stiffness. The traditional method for computing the stiffness is by measuring the static and dynamic modulus of elasticity. Nilsen and Aitcin (1992) established two equations for static and dynamic modulus of elasticity from compressive strength and ultrasonic pulse velocity test results as follows [39].

$$E_c = 0.31\gamma^{1.29} f_c^{0.35} \tag{4}$$

$$E_{\mathrm{d}} = \gamma v^2 \frac{(1+\mu)(1-2\mu)}{(1-\mu)} \tag{5}$$

Also, according to Zhutovsky and Kovler (2017), the dynamic bulk modulus can be determined by the following equation [40]

$$K = \gamma v^2 \frac{(1+v)}{3(1-v)} \tag{6}$$

Where E_c = Static Modulus of Elasticity in MPa

E_{d} = Dynamic Modulus of Elasticity in MPa

K = Dynamic Bulk Modulus in MPa

γ = Density of Concrete in kg/m^3

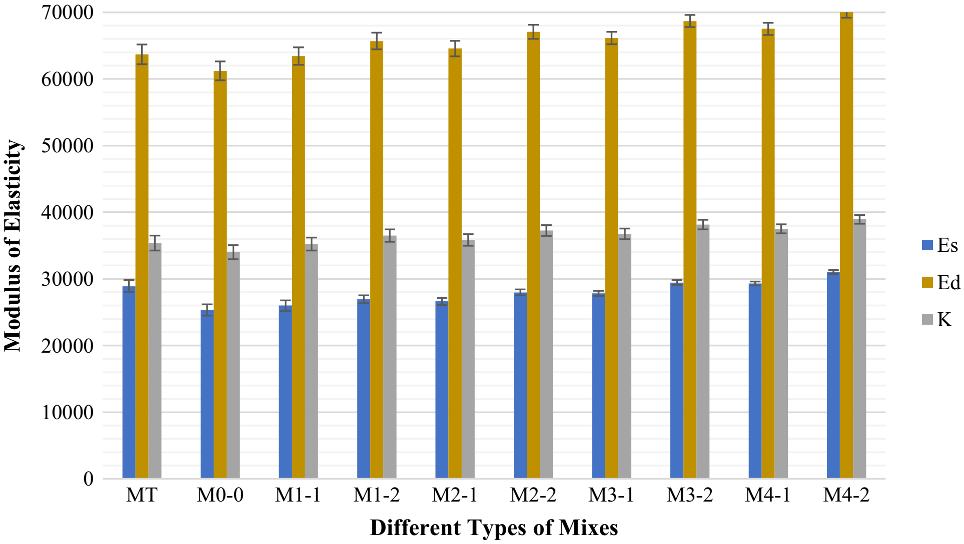
f_c = Compressive Strength in MPa

v = Ultrsonic Pulse Velocity Value

μ = Poissoins Ratio

The density of traditional concrete is taken as 2400 kg/m^3 and Poisson's ratio of traditional concrete μ_T is 0.2. For brick aggregate concrete the density is taken as 2200 kg/m^3 and Poisson's ratio of brick aggregate concrete μ_B is 0.21. The compressive strength and ultrasonic pulse velocity values of concrete for different mixes are taken from Figs. 2 and 3. From, Fig. 5 it can be noticed that when stone aggregate is replaced with brick aggregate in 100%, static and dynamic modulus of elasticity as well as dynamic bulk modulus of brick aggregate concrete decreased as compared to stone aggregate concrete. This happened due to the lower density of brick aggregate concrete as compared to stone aggregate concrete. But when the cement was partially replaced with nanoparticles of alumina up to 4% and water was partially replaced with rubber latex up to 2% in brick aggregate concrete (i.e., mix $M_{0\text{-}0}$), both static and dynamic modulus of elasticity as well as dynamic bulk modulus had improved gradually. The static elastic modulus of elasticity of brick aggregated concrete became more than the traditional concrete, when cement was replaced with nanoparticles by 3% and water was replaced with rubber latex by 2%. But the dynamic modulus of elasticity of brick aggregate concrete crossed the dynamic modulus of elasticity value of traditional concrete, when cement was replaced with nanoparticles by 1% and water was replaced with rubber latex by 2%. But dynamic bulk modulus value was more when simultaneously both cement and water were replaced with nanoparticles and rubber latex, respectively, by 1%. Hence it is recommended that at least 3% of cement should be replaced

Fig. 5 Static Young's modulus, dynamic Young's modulus and dynamic bulk modulus of different mixes



with nanoparticles of alumina and 2% of the water should be replaced with rubber latex in brick aggregate concrete to achieve desired both static and dynamic modulus of elasticity.

Effect of internal curing agents on porosity of concrete mix

The porosity of different mixes obtained from the MIP test after 3 days and 28 days curing are shown in Fig. 6. The traditional concrete prepared from PPC had a higher total pore volume than the other mixes. The sizes of the pores were 0.003–300 µm. This range can be divided into three categories, i.e., macropores (0.33–300 µm), mesopores (0.02–0.33 µm) and micropores (0.003–0.02 µm). But as the brick aggregate was replaced with stone aggregate fully the macropore size decreased and micropore size increased. Because the water stored in saturated brick aggregate gradually released water and contributed to the cement hydration process. The fly ash presented in PPC generated additional hydration product in the form of secondary C–S–H gel by reacting with released water from brick aggregate and filled the capillary pores in that concrete mix ($M_{0\text{-}0}$). It is concluded that the replacement of stone aggregate by brick aggregate is supplying sufficient internal curing water for the cement hydration process and helping to densify the pore structures. But when the nanoparticles of Al_2O_3 partially replaced the cement up to 4%, the voids between fly ash and cement were filled by them by reducing the porosity. As the percentage of nanoparticles increased in concrete, the macropores gradually decreased and the micropores gradually increased for 3 days of curing. But after 28 days of curing sufficient amount of C–S–H gel has formed which is able to close the micropores. Hence in Fig. 3, it has shown that the percentage of sealed pores at three days curing is very low as compared to 28 days curing. When those nanoparticles were contacted with water, it also formed secondary C–S–H gel, which helped to reduce the porosity of concrete. The capillary pores of size 0.01–10 µm were generally found in water-filled spaces in between partially hydrated cement grains [41]. They affected the permeability and strength of concrete. When rubber latex was added in concrete by partially replacing water, it entered in between those pores due to its higher specific gravity and sealed them at the time of hydration. Since the rubber latex has higher specific gravity than water, its molecules settled downward and filled the gaps between both cement and aggregate particles. Since water is lighter than rubber latex it moved upward and deposited at the surface. As time passes the water started to evaporate from the surface layer of concrete and the rubber latex in between the voids slowly converted to solid paste. Due to the evaporation of water, the volume of cement paste tried to decrease but the solid paste obstructed to come close two cement particles to each other. Hence the volume of the total concrete matrix remained unchanged at that portion, where the rubber latex occupied that void space. When 4% of nanoparticles and 2% of rubber latex were introduced in concrete, they sealed 38% pores combinedly after 28 days of curing. This is due to the presence of finer size of alumina particle which forms a capillary tube after drying and hardening. As the water was replaced by rubber latex the diameter size of all types of pores (capillary tubes) decreased. Rubber latex filled the spaces formed by all types of pores and sealed them by forming solid materials at harden stage. Hence both porosity and gel pore size reduced 50% when 2% rubber latex was replaced with water in concrete ($M_{4\text{-}2}$) as compared to traditional concrete without rubber latex (MT). The weight coefficient of all types of pores is showing lower a value for mix $M_{4\text{-}2}$ than other mixes. Most of the micropores are sealed by solid rubber latex. It is concluded that rubber latex can be replaced the water partially or fully in the concrete mix, which can help to increase the workability

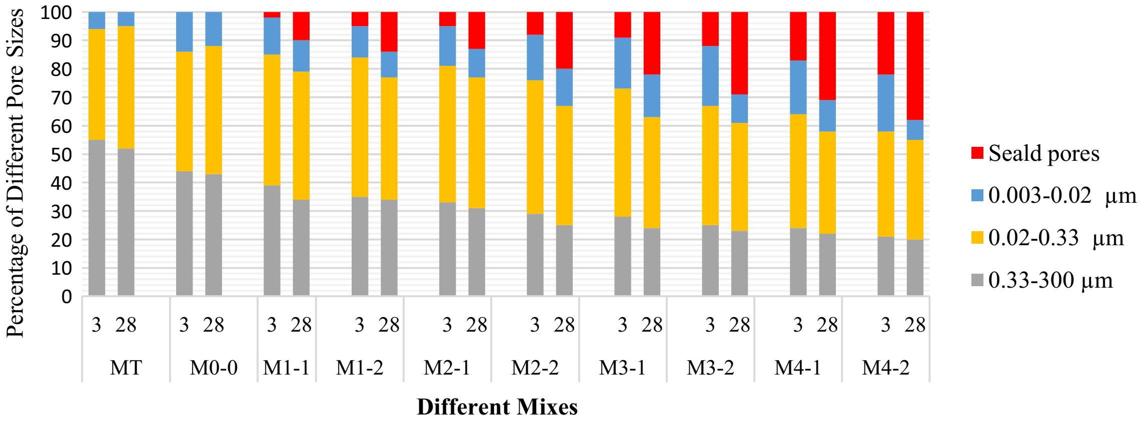


Fig. 6 Effect of internal curing agents on pore volume concretes at 3 and 28 days

and decrease the porosity as well as shrinkage of geopolymer concrete mix as a result strength and durability may be increased and also recommended to use a higher percentage of rubber latex by replacing water for sealing the all-types pores of the concrete. The amount of micropores of 2% rubber latex concrete is less than the 1% rubber latex concrete. Also, from Fig. 3 it is noticed that at 3 days curing all the macropores were converted into mesopores and micropores, after 28 days the solid rubber latex and extra C–S–H gel formed by nanoparticles and sealed all types of pores partly. Hence the amount of mesopores and micropores were more in 3 days curing concrete than 28 days curing concrete. This may result in the effect of internal curing as the promotion of cement hydration by water from the brick aggregate. Due to this additional hydration products had formed. The volumes of capillary pores of different mixes are shown in Fig. 7. Due to the absence of rubber latex in the first two types of mixes (i.e., MT and $M_{0\text{-}0}$) no voids were sealed. Only the macropores converted into mesopores and micropores in $M_{0\text{-}0}$ mix when stone aggregates were replaced by brick aggregate. The PPC concrete possessed a higher volume of capillary pore ranging from 0.01 to 10 µm. The full replacement of stone aggregate with brick aggregate reduced the volumes of pores that had been observed on both 3 days and 28 days concrete specimen. These results were also compatible with 3 days and 28 days compressive strength results, i.e., those mixes that contained smaller capillary pores (positive effects of internal curing on the reduction of porosity) had shown higher compressive strength [42].

Effect of internal curing agents on hydration paste of different mixes

The content of $Ca(OH)_2$ in the concrete of different mixes at 3 and 28 days of curing is determined from Eq. (3). It has been found that the calcium hydroxide content was in less amount in all mixes where the cement was replaced with nanoparticles of Al_2O_3. Because the nanoparticles of alumina form extra C–S–H gel when it comes in contact with water [43]. The mixed content with nanoparticles reacted with fly ash of pozzolana cement and formed extra secondary C–S–H gel getting an extra amount of water released from the brick aggregate. The decrease in calcium hydroxide inside the concrete shows a greater promotion of the hydration process by internal curing. The consumption of $Ca(OH)_2$ due to the pozzolanic reaction of fly ash present in pozzolana cement is shown in Eq. (7).

$$\begin{aligned} \mathrm{CH}_{\text{consumption}} &= \text{CH of the mix which contains}\,\mathrm{Al_2O_3} \\ &\quad * \frac{C}{C+A} - \text{CH of traditional concrete mix MT} \end{aligned} \tag{7}$$

where $\mathrm{CH}_{\text{consumption}}$ = Consumption of calcium hydroxide by pozzolanic reaction (%), C = Cement in kg/m^3 and A = Nanoparticle of Alumina in kg/m^3, $\frac{C}{C+A} = 0.06$.

It has been noticed that the consumption of calcium hydroxide by the nanoparticles during the hydration process was increased with time. The consumption of calcium hydroxide due to pozzolanic reaction of nanoparticles using brick aggregate was 1.5 and 1.2 times higher than that of the traditional concrete for both 3 and 28 days curing, respectively. The calcium hydroxide consumption by pozzolanic reaction of all mixes contained nanoparticles as compared to mix $M_{0\text{-}0}$. It indicates that the full replacement of stone aggregate with brick aggregate accelerated the pozzolanic reaction with nanoparticles increased the consumption of calcium hydroxide. The consumption of calcium hydroxide of all mixes is shown in Fig. 8.

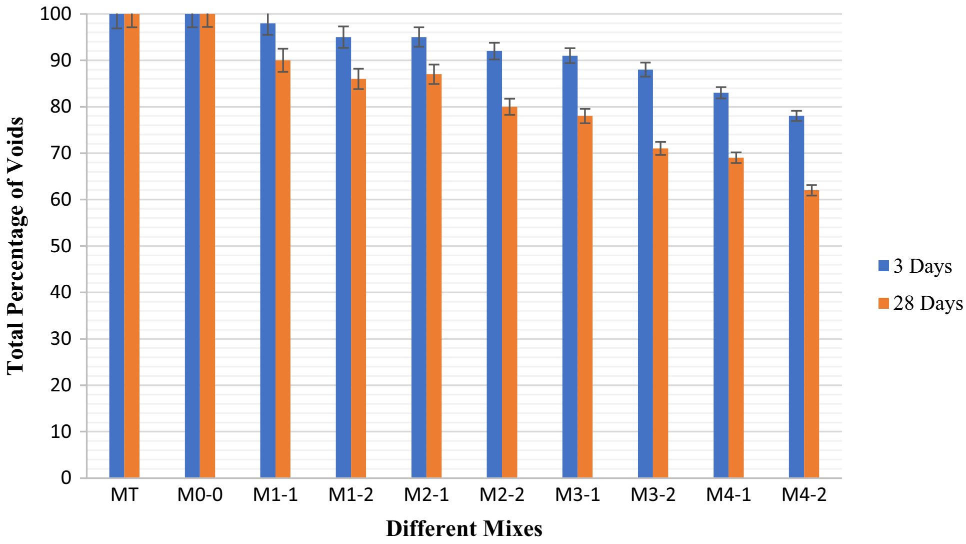
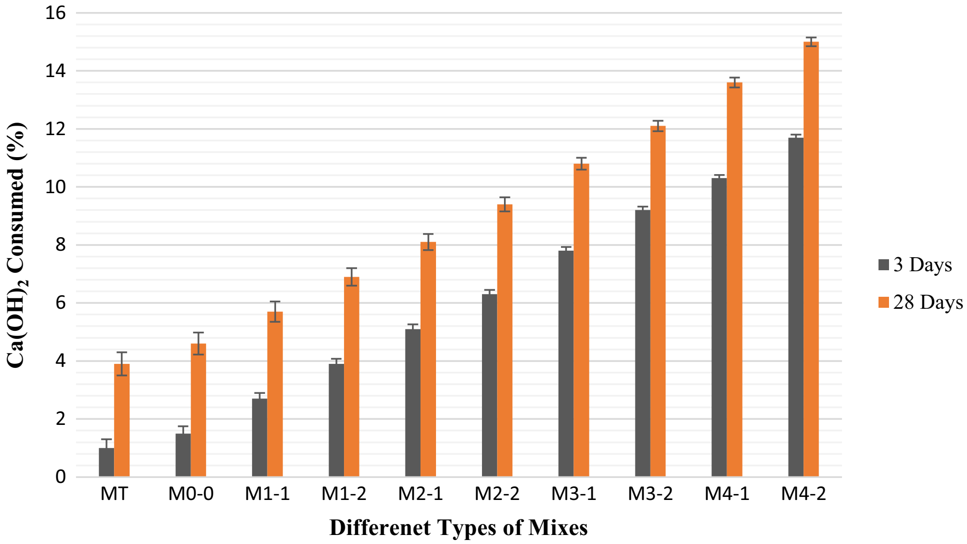


Fig. 7 Total percentage of voids present in different mixes after applying the internal curing agents

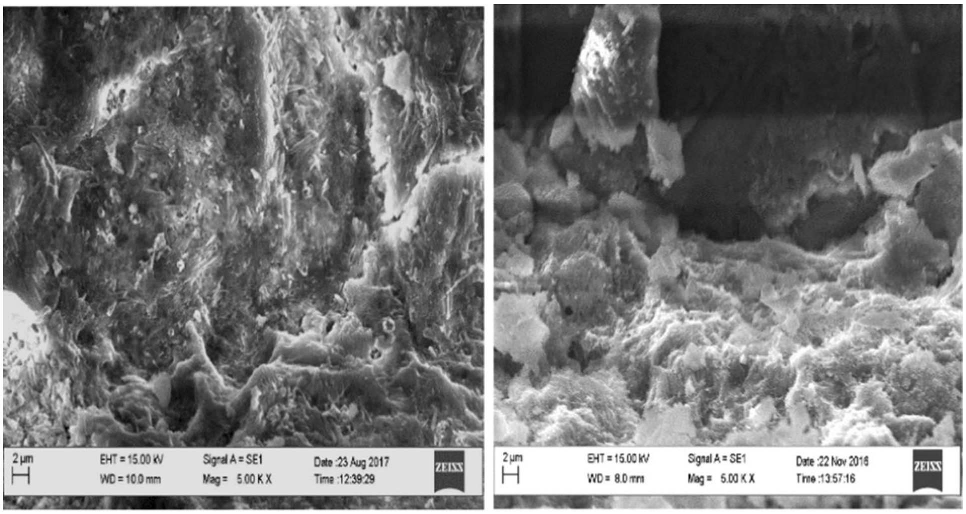
Fig. 8 Consumption of calcium hydroxide by pozzolanic reaction of nanoparticle of alumina and fly ash content in PPC



The pozzolanic reaction of nanoparticles and fly ash accelerated by the internal curing of early days and increased $Ca(OH)_2$ consumption. It was found that the rate of consumption of calcium hydroxide at 3 days curing was more than the 28 days curing. This was happened due to providing of curing process immediately after casting with the help of cotton thread. Hence the hydration process started from the first day of casting. The macropores of size 0.33–300 µm were affected significantly by the internal curing whereas the mesopores of size 0.02–0.33 µm were affected slightly by this new arrangement. Most of the micropores of size 0.003–0.02 µm were sealed by solid rubber latex. From the previous literature, it was found that the volumes of mesopores and micropores may be decreased and increased, respectively, due to the pozzolanic reaction and consumption of calcium hydroxide [44, 45]. As a result, the additional product produced by the pozzolanic reaction of supplementary cementitious materials could fill and reduce the volume of macropores and increase the volume of mesopores slightly. The SEM image of the traditional concrete mix and the brick aggregate concrete mix is shown in Fig. 9.

By examining the SEM image, it has been cleared that the new arrangement of internal curing has several influences on the microstructure of concrete. A compacted microstructure is appearing inside the SEM image within the interfacial transition zone due to the formation of high quantities of C–S–H gel in a later age. One can notice in SEM image that, a large quantity of free water in empty pores in hydrated cement paste is absent due to continuous series of hydration reaction provided by new internal curing technique, may increase the strength of concrete. The few amounts of un-hydrated cement particles in the SEM

Fig. 9 SEM image of concrete without and with internal curing



(a) SEM image of Mix MT **(b) SEM image of Mix M_{0-0}**

image of brick aggregate concrete indicate that a greater achievement of a degree of hydration. A lot of empty coarse pores are seeing in the microstructure of traditional concrete without internal curing indicates about the expectation of self-desiccation in the low water–cement ratio of concrete, i.e., 0.3. It is noticed that many empty pores are surrounded by the residual cement grains known as Hadley grain pores. In brick aggregate concrete with internal curing, it has been found that the water has filled inside the capillary pores in the hydrated cement paste for a long period instead of larger pores of brick aggregate. The higher degree of hydration and absence of macropores might be contributed to higher compressive strength achieved at an earlier age. The brick aggregate reduced the interconnected porosity of the paste matrix. Also, the reduction of early shrinkage of concrete reduced the number of larger pores in brick aggregate concrete. On the other way, a large number of empty pores are seen in traditional concrete without internal curing due to shrinkage and substantially reduces the capillary stresses. The addition of nanoparticle of alumina also decreased the porosity of concrete after 28 days of curing. This happened due to the formation of ettringite in the paste matrix. The long ettringite crystals filled the voids inside the paste matrix. With the help of brick aggregate, the w/c in cement paste slightly increased, which increased the hydration and formation of ettringite; counteracted the initial high level of capillary porosity. The present internal curing process resulted in a dense and impervious paste structure.

From the above results following hypotheses drawn from present internal curing agents are given below.

Al_2O_3 Nanoparticles: These porous superfine materials increased water demands for further hydration process of cementitious materials due to their more fineness.

Brick Aggregate: These prewetted lightweight aggregate increased the degree of cement hydration by releasing the absorbed water whenever it was necessary. That is why denser and less permeable types cementitious paste formed. It reduced the mobility of ions and restricted to growth of microcracks.

Natural Rubber Latex: By mixing with water, it decreased the concentration of fresh concrete mix. Due to this, an osmotic pressure had been developed inside the concrete. Hence the water from the curing tank spontaneously flowed toward the fresh concrete matrix and compensated for the loss of water due to evaporation.

Conclusions

The following conclusion can be drawn from this present research.

(i) The special arrangement of internal curing of concrete in present research not only accelerate the early hydration process but also increased compressive strength, modulus of elasticity, packing density and improved the microstructure of concrete. The provision of a new arrangement resolved the problems of early curing during the period between casting and demolding. The early curing process reduced the evaporation of water from the concrete surface. As a result, the shrinkage and shrinkage cracks in the concrete were reduced and resolved the problems of water shortage for the early as well as later hydration process. Hence the microstructure of concrete improved in a better way within 3 days by reflecting corresponding results of higher UPV and compressive strength w.r.t. traditional concrete which was not provided by the special arrangement.

(ii) A sufficient amount of water had absorbed by pre-saturated brick aggregate and formed a water reservoir tank inside the concrete matrix. That water was utilized at a suitable time, when the concrete demanded it to increase its performance. Due to that extra water supplied by the brick aggregate; workability of concrete increased up to 25%, 3 days compressive strength increased about 4%, the concrete surface was kept moist for a long duration and supplied sufficient water to fly ash and nanoparticle during hydration reaction. The internal curing of concrete with brick aggregates improved the microstructural property of concrete by filling the inner voids with C–S–H gel.

(iii) The replacement of cement with nanoparticles of Al_2O_3 up to 4% played a dual role inside the concrete mix. Initially, it filled the voids between the cement particles and increased the packing density. That is why the surface area of cementitious materials reduced significantly as a result the slump height increased 2.25 times than the traditional concrete. During the hydration process, it produced secondary C–S–H gel by extracting the stored water from the brick aggregate. As a result, the compressive strength of concrete increased up to 37% and 40% corresponding curing of 3 days and 28 days, static Young's modulus increased 7% and both dynamic Young's modulus and bulk modulus increased 10% as compared to traditional concrete. Those secondary C–S–H gel filled the micropores of concrete as a result the UPV value increased about to 9% for both 3 days and 28 days curing. It indicates that the microstructure of concrete had improved in a specific manner which was also verified from the SEM image.

(iv) The rubber latex also played dual roles in the present research. At the initial stage, it accelerated the internal curing process by creating osmotic pressure and increased the workability more than doubled as compared to traditional concrete. At a later age, it sealed near about 35% of the voids by solidifying at harden stage of concrete. As the dose of rubber latex was increased up to 2%, it decreased the percentage of macropores from 55 to 20%, mesopores from 45 to 35% and micropores from 15 to 8%. It indicates that as the dose of rubber latex was increased, it first reduced the macropores and mesopores of the concrete or it might be converted to all macropores and mesopores into micropores. At the latter case, the micropores might be filled by C–S–H gel produced by nanoparticles and fly ash of PPC concrete.

Limitations and future scope

This special type of arrangement for internal curing is a little bit difficult to apply for cast in situ of the concrete structural member at the site. It may be more complicated to provide a continuous curing process in this manner to high-rise buildings. This technique is suitable for precast concrete blocks only.

In this research rubber latex is a miracle ingredient that remains liquid state at the time of collection from the plant and becomes solid after the mixing of concrete. The liquid state of rubber latex helps to prepare a homogeneous mixture at the time of mixing and sealed to all the voids at the time hardening of concrete. In the present research, the percentage of rubber latex has taken as 2%. A hence higher percentage of replacement of water with rubber latex should be studied.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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