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Influence of raw greywater on compressive strength of concrete

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Abstract. Raw greywater, as an alternative water source, was used in concrete production with an aim to save the freshwater sources. Therefore, the variations of compressive strength, the most important and impact causing property of the concrete as regards to its quality and service, were assessed. Greywater was collected from a household where blackwater and greywater were separately disposed of. Total 162-cylinder specimens were cast by using the collected greywater and freshwater (municipally supplied tap water). The specimens were tested for compressive strength after 7, 14 and 28 days of curing. The investigation was carried out considering several experimental conditions: difference in the quality of water in the casting phase, curing phase and casting-curing phase and, also in types of coarse aggregates. A total of 28 water quality parameters (physical, chemical and biological) were tested for both greywater and freshwater. Some tests (turbidity, salinity, solids, organic matter, ammonium, nitrate, phosphate, calcium, magnesium, potassium, sodium, and zinc) exhibited higher (about 2 to as high as 1800 times) and a few others (dissolved oxygen, chloride and iron) showed lower values (about 5 to 8 times) for greywater in comparison to freshwater were decreased. The compressive strength of concrete decreased by about 20 % when greywater was used in the casting-curing phase. Whereas, this reduction was found to be only up to 4 % when greywater was used in the casting phase. Raw greywater could be used in concrete for some specified structures considering its lower strengths as found in this study. But in such cases, the impact of the greywater on other important characteristics of concrete and the consequent changes in the phase-structural parameters of the material also need to be clarified through further research.

1. Introduction

Freshwater scarcity boosts to consider wastewater as a resource in recent days. On one side, the uses of untreated or treated wastewater lessen the pressure on freshwater sources and on the other side, help manage the substantial amount of generated wastewater effectively to ensure sustainable environmental protection [1]. Literature reports that raw and/or treated wastewater is considered as a non-conventional water resource and contributed 70 million cubic meters per year if managed properly [2]. Therefore, replacement of freshwater by using some specified wastewater (raw or in treated condition) in different water-consuming sectors is becoming reality and among all types of wastewater, greywater becomes the first choice for this purpose.

Greywater means that part of domestic wastewater originating from non-toilet activities in a household such as baths, showers, hand basins, washing machines, dishwashers, and kitchen sinks [3–5]. Due to having less polluted quality (contains only 30 % of the organic fraction, lower pathogen content and 9–20 % of the nutrients) rather than other types of wastewater but of vast generation (70–80 % of total domestic wastewater), greywater is already widely used in different non-potable sectors instead of freshwater such as toilet flushing, car washing, landscaping, plant watering, agricultural irrigation of non-food crops, ornamental fountains, fire protection, air conditioning and alike. [3, 6–12].

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Concrete (a composite, versatile construction material made from a mixture of cement, aggregates, and water; can be easily produced and fabricated which hardens and attains considerable strength within a short time) in manufacturing sector plays a major role in world's infrastructure development where water is a vital issue in both mixing phase (a procedure of homogeneous mixing of water and other materials that ensures high quality of concrete) and curing phase (a procedure for ensuring the hydration of the cement in newly placed concrete keeping controlled moisture loss and sometimes temperature that increase concrete strength and abrasion resistance, lessen the concrete scaling, surface dusting and cracking) as well [13–16]. Water is an unavoidable ingredient in the concrete manufacturing sector and consumes a substantial amount of freshwater (industry alone consumes more than one trillion gallons water per year worldwide without including wash water and curing water [17], another statistic reports that approximately 150 liters of water are required per cubic meter of concrete production, without considering other applications of water in the concrete industry [18]). Therefore, the use of non-fresh water in the aforementioned sector could be an option of saving precious and scarce freshwater resources. Although the use of several non-fresh water sources in concrete production is reported in existing literature such studies were limited in numbers that include: partially processed wastewater from a sewage treatment plant, industrial wastewater, domestic wastewater, wastewater coming from a ready-mixed concrete plant, etc. [18–23].

Besides, not only in terms of quantity but water is also worth in concrete in terms of quality as it actively participates in the chemical reactions of the hydration process of cementation materials and curing [24, 25]. The present impurities of water that used in mixing and/or curing phases of concrete production may interfere with the setting time of the cement, may affect shrinkage, the durability of concrete, and may also lead to corrosion of the reinforcement [26]. Therefore, the quality of the water needs to be carefully elucidated while using concrete. Although, in terms of quality, usually potable water (the water which is drinkable i.e. free from physical, chemical and biological impurities) is considered as an ideal one for casting and curing of concrete as most of the codes and specifications recommended such criterion for its known chemical composition and well-regulated [2, 27–29], but these specifications may not be the best basis for evaluation of the suitability of water as mixing and curing water. Some waters which do not meet potable criteria but reasonably clean and free from oil, acid, and other deleterious chemical substances, have been found to produce concrete of satisfactory quality [30]. Furthermore, as the most widely used material worldwide with a substantial amount of water consumption, the concrete manufacturing sector should take the environmental and societal responsibility to ensure sustainable development as well [18].

Therefore, keeping in mind the protection of natural water resources, the use of greywater, in terms of both quantity and quality, in concrete production could be examined as its degree of impurity is much lower but with significant quantity. Moreover, this research would be more practicable in Bangladesh context, as the country is on the edge of entering the directory of water-stressed countries and at the same time it is developing vastly in terms of infrastructures from last few decades to achieve its development mark "RUPOKOLPO (*VISION) 2041*".

The main objective of this study was to assess the possible use of raw greywater in concrete production in terms of compressive strength since this is considered as the most important and impact causing property of the concrete so long its quality and service are concerned [31, 32]. Consequently, the specified tasks included as follows:

Firstly, the collected raw greywater and freshwater were characterized physico-chemically and compared with the standard limits set as different concrete manufacturing codes and specifications worldwide. Then, these waters were used in different phases (e.g., casting-curing phase, casting phase, and curing phase) of concrete production. Finally, the variations in compressive strengths were evaluated to justify the possibility of the use of raw greywater.

2. Methods

2.1. Water Sampling

About 120 liters of greywater was collected from an outlet, before entering sewage line, of a residential building located in Matuail, Jattrabari, Dhaka, (23.697206N, 90.471151E) where blackwater and greywater were separately discharged. Fig. 1 shows the location of the greywater sampling source. Freshwater was collected from a tap in the University of Asia Pacific, supplied by the Dhaka Water Supply Authority (DWASA).

Collected sample waters were used for specimen casting and curing. Therefore, both tap water and greywater were characterized in terms of their physical, chemical and biological properties. Consequently, a total of 30 different water quality parameters were selected and tested for greywater and freshwater. The tested parameters include pH, Dissolved Oxygen (DO), Temperature, Color, Turbidity, Hardness, Salinity, Total Suspended Solids (TSS), Total Dissolved Solids (TDS), Total solids, Alkalinity as $CaCO_3$, Conductivity, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Phosphate, Nitrite, Nitrate, Ammonia, Chloride, Sulphate, Cadmium, Calcium, Copper, Iron, Lead, Magnesium, Nickel, Potassium, Sodium, and Zinc.

2.2. Water Quality Parameters Testing

Water quality parameters pH, DO and Eh values were measured with an HQ 40d multi parameter-189 and PHC3OH, LDO101 and MTC101 probes respectively supplied by HACH company.

Analyses of NH_4-N, NO_2-N, NO_3-N, TP, TSS, SO_4^{2-}, COD and color compounds were carried out using HACH 2800, HACH 1900 spectrophotometers and a HACH DRB 200 reactor block based on standard procedures, as highlighted by the supplier. BOD_5 measurement was carried out with manometric instruments (HACH BOD TRAK II) and incubators operated at 20°C. Cadmium, Calcium, Copper, Iron, Lead, Magnesium, Nickel, Potassium, Sodium, and Zinc were measured by using Atomic Absorption Spectrophotometry (AAS). All the tests except heavy metals were performed at Environmental Engineering Laboratory, University of Asia Pacific (UAP) and heavy metals were tested in the laboratory of NGO Forum for Public Health, Bangladesh branch.

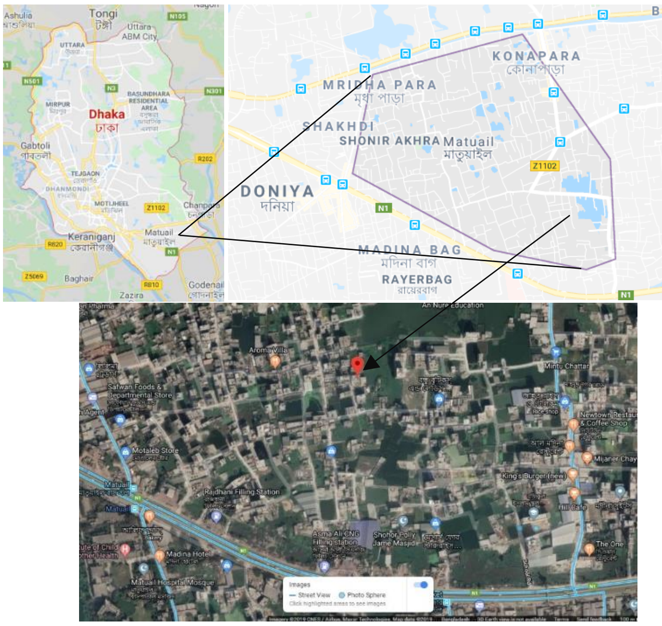

Figure 1. Greywater sampling location.

2.3. Concrete Materials Collection

Coarse aggregates (CA) (Standard brick chips and stone chips made from standard quality bricks and stone materials, respectively) and fine aggregate (FA) (Sylhet sand) were collected from the local market (namely, Gabtoli Beribadh) in Dhaka. Cement (Ordinary Portland Composite, Seven Rings Cement Brand, one of the popular brands of cement in Bangladesh having specifications and composition of BDS EN 197-1:2003, CEM II/B-M(S-V-L), Grade – 42.5 N/mm^2; Clinker – 65 %–79 %; Slag, fly ash and limestone – 21 %–35 %; Gypsum – 0 %–5 %) was collected from a local market.

2.4. Materials Properties and Mix Design of Concrete

Coarse aggregates, having a rough texture and angular shape, were crushed manually as a size of 20 mm (3/4 downsize). Unit weight test, specific gravity test, sieve analyses were done for both CA and FA using ASTM C127 and ASTM C136 standard methods. Both brick chips and stone chips were washed properly to avoid dust and other impurities before performing any tests. Besides, saturated surface dry conditions of the aggregates were ensured for the casting of the specimen. A volumetric concrete mix design was carried out with a ratio of 1:1.5:3 (Cement: FA: CA) having a water-cement ratio of 0.5. Table 1 showed the physical properties of the materials used in the concrete mix design.

Table 1. Physical properties of concrete materials.

Aggregates		Bulk sp. gr.	Fineness modulus
Coarse	Stone	2.64	--
	Brick	2.09	--
Fine	Local sand	2.48	2.52

2.5. Specimen Casting, Curing, and Testing

Total 162 cylindrical specimens (8” * 4”) of six different experimental cases (differences in casting water and curing water (freshwater and greywater) and coarse aggregates (brick chips and stone chips)) were prepared (Table 2) with the above-mentioned mix design. Specimens of two cases (FBF (1st letter for casting (mixing) water, 2nd letter for coarse aggregate, 3rd letter for curing water, i.e., FBF: casting with fresh (tap) and curing with fresh (tap) water and use of brick chips as coarse aggregate) and FSF) were cast and cured with freshwater and with similar preparation to serve as a control to the others cases. Before casting, the coarse aggregates were kept 24 hours in tap water for FBF and FSF specimens and those were kept in greywater for FBG, GBG, FSG and GSG specimens for 24 hours. After that the aggregates were separated from water and kept to dry for some times in the room temperature ensuring SSD condition. After casting of each case, the specimens were left to dry for 24-hours and then remold and cured for specified days in specified waters. Compressive strength was tested using ASTM C 39 method after curing of 7 days, 14 days and 28 days. All the tests were performed at Engineering Materials Laboratory, University of Asia Pacific (UAP).

Table 2. Specimen details.

ID Name*	Casting water	Curing water	Coarse Aggregate	Nos. of specimens
FBF	Tap	Tap	Brick	27
FSF	Tap	Tap	Stone	27
GBG	Grey	Grey	Brick	27
GBF	Grey	Tap	Brick	27
GSG	Grey	Grey	Stone	27
GSF	Grey	Tap	Stone	27

**1st letter for casting (mixing) water, 2nd letter for coarse aggregate, 3rd letter for curing water e.g. GBF: casting with greywater but curing with fresh (tap) water and use of brick chips as coarse aggregate.*

3. Results and Discussion

3.1. Characteristics of greywater and freshwater

Table 3 summarized the quality of greywater and freshwater (municipality supplied tap water) used in this study. The greywater quality data showed significantly higher concentrations compared to freshwater (2 to 1800 times higher) in the parameters include turbidity, salinity, solids, organic matter, ammonium, nitrate, phosphate, Ca, Mg, K, Na and Zn whereas the concentrations of DO and Fe were low. Comparing with other greywater standards from the literature it could be characterized as weak to medium strength in terms of pollution [33].

Table 3 also presented the permissible limits of each quality parameter of water that can be used in concrete production. It is found that the concentrations of all the constituents of greywater were within the respective permissible limits.

Table 3. Water quality details.

Water quality parameter	Unit	Tap water	Greywater	Limit	References
				3	[34, 35]
				> 5	[36, 37]
pH	--	6.58	5.59	6	[38]
				6-8	[39]
				7-9	[40]
Dissolved Oxygen (DO)	mg/L	5.06	0.61	--	--
Color	Pt-Co	5	18	--	--
Turbidity	JTU	17.62	260.59	2000	[30]
Salinity	mg/L	0.1	0.2	--	--
				50000	[41]
Total Solids (TS)	mg/L	179.6	384	5000-10000	[42]
				4000	[35]
Total Suspended Solids (TSS)	mg/L	8	193	2000	[38, 43, 44]

Water quality parameter	Unit	Tap water	Greywater	Limit	References
Total Dissolved Solids (TDS)	mg/L	171.6	191	50000	[45]
				2000	[38, 40, 43]
				< 6000	[30]
Biochemical Oxygen Demand (BOD)	mg/L	< 0.2	360	--	--
Chemical Oxygen Demand (COD)	mg/L	1.2	1420	--	--
Nitrate	mg/L	0.001	0.004	500	[46]
Nitrite	mg/L	0.3	0	--	--
Total Hardness	mg/L	137	118	--	--
Alkalinity as $CaCO_3$	mg/L	132	117	500	[40]
				1000	[39, 44]
Chloride	mg/L	< 60	< 60	360	[47]
				500	[36, 37, 43]
				2000	[38]
				4500	[46]
Conductivity	S/m	356	39.5	--	--
Copper	mg/L	< 0.01	0.26	500	[44]
				600	[29]
Sulphate	mg/L	< 1	< 1	400	[38]
				600	[47]
				1000	[36, 46, 48]
				2000	[36, 37, 45]
				3000	[41]
Total Phosphate	mg/L	0	10.1	100	[36, 46]
Cadmium	mg/L	< 0.002	< 0.002	--	--
Calcium	mg/L	14.7	82	2000	[40]
Iron	mg/L	2.44	0.45	--	--
Lead	mg/L	< 0.05	0.002	100	[46]
				500	[44]
				600	[29]
Magnesium	mg/L	9	20	2000	[40]
Potassium	mg/L	3.1	8	2000	[40]
Sodium	mg/L	13.2	90	2000	[40]
Zinc	mg/L	< 0.005	0.09	100	[46]
				500	[44]
				600	[29]

3.2. Compressive strength of concrete: Effect of casting-curing water (FBF Vs GBG; FSF Vs GSG)

Fig. 2 showed the effect of the quality of water on the compressive strengths of concrete. Utilizing brick chips as coarse aggregate the compressive strengths of concrete were found 16.6 ± 0.9 MPa, 19.5 ± 0.5 MPa and 23.8 ± 1.5 MPa after 7 days, 14 days and 28 days curing respectively using greywater as casting-curing water (GBG) (Fig. 2a). In contrast, in FBF (using tap water as casting -curing water with brick chips), the corresponding values were found 20.0 ± 0.5 MPa, 24.5 ± 0.7 MPa and 29.6 ± 0.6 MPa. Therefore, while replacing tap water (conventionally considered as freshwater for concrete production in Bangladesh) with greywater the strength reduced by 17.0 %, 20.4 % and 19.6 % in 7 days, 14 days and 28 days curing period respectively (Fig. 5a). Similarly, using greywater with stone chips as coarse aggregate (GSG) the strengths in 7 days, 14 days and 28 days curing period were found 15.2 ± 0.7 MPa, 19.8 ± 0.6 MPa and 22.5 ± 0.7 MPa, respectively. Corresponding results in the case of tap water (FSF) were 19.2 ± 0.3 MPa, 24.9 ± 0.4 MPa and 28.7 ± 0.3 MPa, respectively (Fig. 2b). These exhibited consistent strength reduction trend in compressive strengths of concrete having values of 20.8 %, 20.5 % and 21.6 %, respectively (Fig. 5b). These results (strength reduction of around 20 %) are not so much undesirable as in literature it is stated that the acceptable level of unknown water compressive strength of concrete is about 20 % of potable water [29]. The trend in increment in the compressive strengths was clearly found with the increment of the curing ages for all cases having similar qualities of water.

Fig. 2 also showed the changes in density with the quality of water. Density was reduced by 2.3 % (from 2148.8 ± 30.7 Kg/m^3 to 2099.7 ± 20.1 Kg/m^3), 0.5 % (from 2118.3 ± 15.4 Kg/m^3 to 2107.2 ± 37.8 Kg/m^3) and 1.2 % (from 2132.6 ± 31.9 Kg/m^3 to 2106.6 ± 26.2 Kg/m^3) for curing periods of 7, 14 and 28 days, respectively for greywater with brick chips as coarse aggregate (Fig. 2a). Corresponding strength's reduction were 2.0 % (from 2374.0 ± 28.0 Kg/m^3 to 2326.6 ± 7.3 Kg/m^3), 2.2 % (from 2366.7 ± 37.8 Kg/m^3 to 2315.2 ± 40.6 Kg/m^3) and 3.0 % (from 2369.4 ± 35.7 Kg/m^3 to 2299.2 ± 12.3 Kg/m^3), respectively for greywater and stone chips (Fig. 2b). It was evident that a percent reduction was found higher in the case of stone chips.

3.3. Compressive strength of concrete: Effect of casting water (FBF vs GBF; FSF vs GSF)

The effects of the quality of casting water on the compressive strength of concrete were shown in Fig. 3. The compressive strengths of concrete were found 17.2 ± 0.5 MPa, 19.7 ± 0.4 MPa and 26.5 ± 1.1 MPa after curing periods of 7, 14 and 28 days, respectively with greywater as casting water and brick chips as coarse aggregate (GBF) (Fig. 3a). These indicate the strength reductions of 14.0 %, 19.6 % and 10.5 % respectively (Fig. 5b) comparing with the FBF case.

On the other hand, the use of greywater with stone chips (GSF) the strengths in 7 days, 14 days and 28 days curing period were obtained 19.1 ± 1.6 MPa, 23.1 ± 1.1 MPa and 27.6 ± 2.9 MPa, respectively. These indicated the reductions of 0.5 %, 7.2 % and 3.8 % respectively (Fig. 5b) in compressive strengths.

Fig. 3 also showed the changes in density with the quality of casting water. Density was reduced by 1.4 % (from 2148.8 ± 30.7 Kg/m^3 to 2119 ± 19.0 Kg/m^3), 0.3 % (from 2118.3 ± 15.4 Kg/m^3 to 2112.9 ± 7.5 Kg/m^3) and 1.5 % (from 2132.6 ± 31.9 Kg/m^3 to 2101.1 ± 12.4 Kg/m^3) with use of greywater and brick chips (Fig. 5a) and 2.1 % (from 2374.0 ± 28.0 Kg/m^3 to 2325.1 ± 6.6 Kg/m^3), 1.5 % (from 2366.7 ± 37.8 Kg/m^3 to 2331.2 ± 22.7 Kg/m^3) and 0.6 % (from 2369.4 ± 35.9 Kg/m^3 to 2354.0 ± 23.7 Kg/m^3) with use of greywater and stone chips (Fig. 5b) in 7 days, 14 days and 28 days curing period respectively.

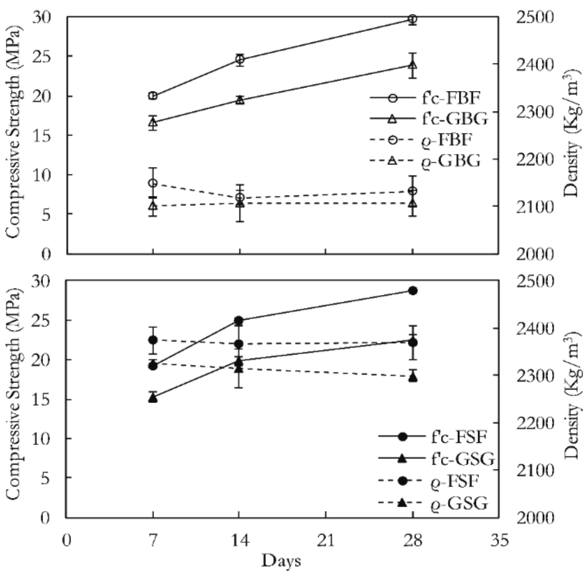

Figure 2. Compressive strengths of concrete made with tap water and greywater a) brick chips as coarse aggregate b) stone chips as coarse aggregate.

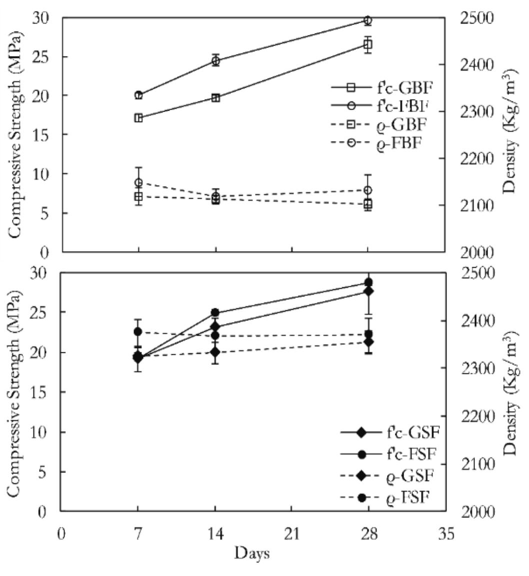

Figure 3. Compressive strengths of concrete with casting water difference a) brick chips as coarse aggregate b) stone chips as coarse aggregate.

3.4. Compressive strength of concrete: Effect of curing water (GBF vs GBG; GSF vs GSG)

The variation of compressive strengths with the variation in the quality of curing water was shown in Fig. 4, although greywater was used during the casting phase of concrete. The compressive strengths of concrete reduced by 3.5 %, 1.0 % and 10.2 % in 7 days, 14 days and 28 days curing respectively with the use of greywater in curing phase and brick chips as coarse aggregate (GBF) (Fig. 4a).

On the other hand, with the use of greywater and stone chips (GSF) the reduction of strengths in 7 days, 14 days and 28 days of curing period were 20.4 %, 14.3 % and 18.5 % respectively (Fig. 5b).

Fig. 4 also showed the changes in density with the changes in the quality of curing water. Utilizing greywater and brick chips, no significant reduction of density was observed but 2.3 % reduced with the use of stone chips as coarse aggregate only in 28 days curing period.

3.5. Compressive strength of concrete: Effects of coarse aggregates

Fig. 5 showed the comparison of compressive strengths of concrete with stone chips and brick chips as coarse aggregate. It was found that the increasing trends of compressive strengths with time were the same between the cases (FSF and FBF, GSG and GBG, GSF, and GBF. The strengths did not vary remarkably when stone chips were used instead of brick chips, except for the cases GBF and GSF. Compressive strength was found higher with stone chips (GSF) rather than with brick chips (GBF) and that was typical.

3.6. Failure pattern of specimen

The fracture pattern of cylindrical specimens was recorded during the experiment. The fracture pattern confirmed the combined failure of the specimens in each of the six cases (Fig. 6).

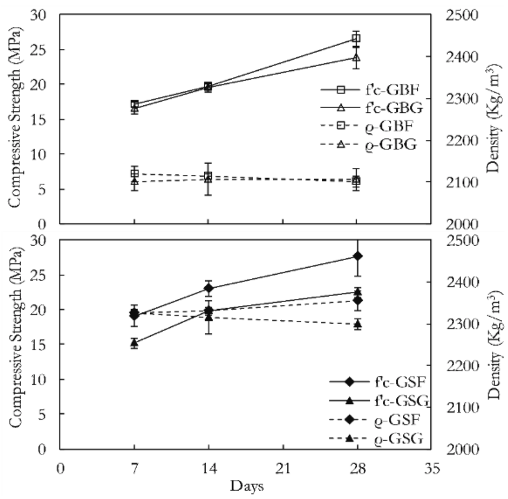

Figure 4. Compressive strengths of concrete with curing water difference a) brick chips as coarse aggregate b) stone chips as coarse aggregate.

3.7. Compressive strength of concrete: Effect of water quality parameters

High concentrations of solid contents (total solids), organic contents (BOD, COD) and heavy metals (Ca, Mg, Na) and very low concentration of dissolved oxygen in greywater might influence to reduce the compressive strengths of concrete.

It is reported in the literature that the concentrations of Ca, K, Na help to increase the rate of hydration reaction which facilitated the early increment of compressive strength, but later, a reduction is witnessed due to their excessive quantities [49]. A high concentration of Mg also causes the deterioration of concrete [50]. In this study the Mg concentration in greywater was 20 mg/L which was more than three times higher than that of tap water. Like magnesium, a high concentration of calcium can also lead to destructive crystal growth in concrete. Calcium also helps to form complex salts composed of $CaCl_2$, $Ca(OH)_2$ and $CaCO_3$ [51,52]. In this study, the concentrations of Ca, K and Na in greywater were found higher around six times, three times and seven times, respectively. These might be the reasons for reducing the compressive strength of the concrete.

It has been found that oxygen plays a significant role in the chemical reactions during concrete manufacturing. The DO concentrations were 5.06 mg/l and 0.61 mg/l in tap water and greywater respectively. This substantial lower amount of oxygen could have affected the hydration process that might have reduced the strength as well.

In the case of pH value, it is reported that the ideal pH range in mixing water for concrete is slightly basic i.e., between 7.2 and 7.6 [29]. In this study, the pH of tap water was 6.58 and that of greywater was 5.59. More acidic conditions of greywater rather than tap water could have influenced the reduction of the compressive strength and this phenomenon also agrees with the literature [53].

Significantly high concentrations of biologically and chemically degradable organic contents (BOD, COD) could be another reason for such a strength-reduction phenomenon, although no standard limits were found for the organic contents in any codes and specifications (Table 3).

4. Conclusions

The effects of using raw greywater on compressive strength of concrete were investigated targeting to save freshwater. Greywater was used during the casting phase, curing phase and casting-curing phases of concrete production. The following conclusions could be drawn:

1. In terms of pollution load, raw greywater could be characterized as "weak to medium." However, its physico-chemical properties met the limits set by the relevant codes and specifications for using water in concrete production.

2. Compressive strength reduced about 20 % with the use of greywater instead of fresh (tap) water in the casting-curing phase with brick chips. Negligible variations in compressive strengths were observed with stone chips instead of brick chips.

3. Compressive strength decreased by 10.5 % when greywater was used in the casting phase only with brick chips. This reduction was lower (3.8 %) with stone chips as coarse aggregate.

4. Compressive strength decreased by 10 % when greywater was used in the curing phase only with brick chips. This reduction was found much higher (up to 18.5 %) with stone chips as coarse aggregate. Although in these compared cases greywater was used in the casting phase rather than freshwater.

5. Regardless of the water sources, the compressive strength of concrete increased with an increase in curing age.

6. An almost similar trend like compressive strengths, i.e., reduction in densities was also found in all phases.

7. Excessive concentrations of solids, turbidity, organic contents, nutrients, calcium, sodium, potassium and magnesium and a substantially lower amount of dissolved oxygen might be the affecting factors on compressive strength and density.

8. Raw greywater could be used in concrete for some specified structures considering its lower strengths as found in this study. But in such cases, the impact of the greywater on other important characteristics of concrete and the consequent changes in the phase-structural parameters of the material also need to be clarified through further research.

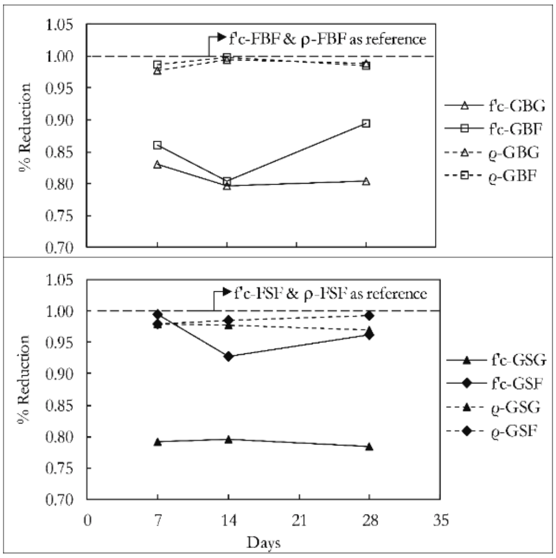

Figure 5. Reduction of compressive strengths of concrete a) brick chips as coarse aggregate b) stone chips as coarse aggregate.

Figure 6. Specimen fracture pattern after compressive strength test.

5. Acknowledgment

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