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RESEARCH ARTICLE

Influence of SCM on the Permeability of Concrete with Recycled Aggregate

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Abstract

The article presents experimental analysis of concretes mixed by using natural and low quality recycled concrete aggregate (RCA). The resistance of concretes with both, RCA and supplementary cementitious materials (SCM) to penetration in aggressive environmental conditions was studied. The influence of fly ash, microsilica and metakaolin on the concrete permeability was investigated. Besides the fundamental mechanical properties of concrete, sorptivity, water absorption, depth of penetration of water under pressure and chloride migration coefficient were tested. The significant effect on the permeability of RCA and SCM is described and discussed. The replacement of the natural aggregate by RCA decreased the concrete resistance to penetration of aggressive media, but the application of the SCM significantly reduced this negative impact.

Keywords

recycled concrete aggregate · supplementary cementitious materials · concrete durability · permeability

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1 Introduction

Increasing the use of recycled concrete aggregate (RCA) and supplementary cementitious materials (SCM) in concrete industry can considerably enhance the environmental friendliness of concrete production. The availability of natural sources of aggregates, which makes up about 60%-70% of concrete volume, is becoming more limited due to restrictions on quarrying operations and longer hauling distances. The disposal of old concrete, which remains from demolished structures, is still a problem and frequently it is deposited in the landfills [1]. So a growing trend to replace the traditional concrete constituents with more sustainable materials is increasingly present in concrete technology. Using RCA as a substitute for natural aggregates and SCM as a partial cement replacement in concrete mixtures is a way to potentially address the economic and environmental concerns.

Dosho 2007 [2] wrote about papers on recycled aggregate concrete that has been published just after World War II: physical properties by Glruzhge in 1946, Russia, and the influence of mixture impurities by Graf in 1948, Germany. First detailed test results on application of the RCA in concrete technology were published by Nixon in 1978 [3]. He suggested that the main field in which more information about the behaviour of the recycled concrete is required is its durability. The studies on the application of RCA into concrete mixture have mainly concerned mix design [4, 5], mechanical properties [6–8], structural performance [9, 10] and the final purpose [11, 12]. Until now many of the durability parameters have been investigated and technological recommendation and detailed requirements according to quality of RCA has been drawn [13]. It has been stated that is possible to design and prepare durable concretes by using adequately good quality RCA. The aggregate characteristics of density, porosity and water absorption are a primary focus in determining the proper concrete mixture and the required concrete properties. These characteristics should be known to limit water absorption capacity of aggregates to no more than 5% for structural concrete, and thus the proportion of RCA is often limited in concrete mixes [13, 14].

Most of the research concerning RCA quality and the durability of concrete mixed by using RCA has been performed in countries where the technical culture has achieved high level. As a consequence the quality of RCA is also high. In some countries certain existing concrete structures (mainly those of minor importance: pavements, savage system elements but also some industrial structures) has been made of poor quality concrete [15, 16]. Obtaining from these structures a good quality RCA, that would meet vital requirements, can be a real problem. Some of these problems caused by usage of poor quality RCA has been already signalled above.

In many countries a large amount of the RCA does not meet the quality requirements [17, 18] and this kind of aggregate is treated as low-quality RCA. Despite the poor quality of the RCA, some research concerning its application in concrete technology was carried out, but it concentrated only on the various techniques and method that can enhance the physical properties of low-quality RCA [18–21]. Tsujino et al. [22] tested the possible applicability of low-quality recycled aggregate treated with oil-type surface improving agent. A surface improving agent reduced water absorption of low- and middle-quality recycled aggregate. Jaskulski [23] tested the possibility of improving the quality of RCA with water glass impregnation, but the results are ambiguous. The polymer based treatments technique were also applied to improve the water permeability of concrete with RCA. The application of these treatments on RCA showed a positive effect on water absorption capacity of RCA [24]. Also the effect of incorporation of colloidal nano-silica on the behaviour of concrete containing 100% recycled coarse aggregate has been studied [25]. The results of experimental investigation showed that compressive strength, tensile strength and non-destructive parameters were enhanced due to addition of nano-silica. Most of the research concerning the possible application of the low-quality RCA in concrete technology was focused on the mechanical properties of concrete [13, 22]. The durability of concrete made with low-quality RCA has not been considered. Permeability of concrete is one of the most important factors influencing durability of concrete with recycled aggregate. The results presented by Zakaria and Cabrera, [26] indicated that concrete with crushed demolition waste (brick) compared with concrete made with fly ash clay artificial aggregate showed almost equal oxygen and water permeability.

In this paper results of the permeability tests of concrete made with low-quality RCA was presented. The main objective of the research was to evaluate the effects of using both, RCA as a replacement for natural coarse aggregate and SCM as cement replacement, on the permeability of concrete. The presence of SCM's in concrete mixture can positively contribute to reduce the permeability of water and chloride ions into concrete [27]. Studies demonstrated that the addition of natural pozzolana may reduce the chloride diffusion coefficient of concrete by three times. Addition of fly ash has an even more significant effect on the diffusion coefficient due to the reduction of permeability and diffusivity of concrete [28].

2 Experiment

2.1 Materials

Eight concrete mixtures were designed and prepared. Ordinary Portland Cement CEM I 32.5 and supplementary cementitious materials: fly ash Class C (FA), silica fume (SF) and metakalion (MK) were used, respectively 50%, 10% and 10% of the cement mass in the reference concretes (I and I R respectively). Chemical and physical properties of the binding materials are presented in Table 1.

In the reference concrete series (I-IV) the natural aggregate fraction 0-2 mm (river sand) and 2-16 mm (gravel) were used. The recycled aggregate was applied in concrete series I R to IV R. RCA was obtained by crushing 25 years old concrete pavement plates in laboratory crusher. The nominal size of recycled aggregate was 2-16 mm. Aggregate crushing value (AVC) was determined according to [30] (similar to [29] but with metrical set of sieves) reached 24.6% for 4-8 mm fraction, 27.0% for 8-16 mm fraction and 21.8% for RCA in general. For natural aggregate ACV was: 5.06% for 4-8 mm fraction, 9.02% for 8-16 mm fraction and 2.84% for the whole aggregate (4-16 mm). The AVC results for utilized RCA fall within a similar range to those presented in the literature [31–34]. All aggregates was used at air dried conditions. A high range water reducer (HRWR) based on polycarboxylates were used. The dosage of superplasticiser was 1.5% of the mass of the binder. Regular tap water was used as mixing water. The water to binder ratio was 0.5 for ordinary concrete and 0.4 for concretes which contained SCM. The mixture proportions of concretes are shown in Table 2.

Concrete specimens were cast in steel moulds and underwent double vibration on vibration table. After demoulding specimens were water-cured in the laboratory for 28 days. After 28 days of curing specimens were stored in the laboratory in temperature 20±2C and RH = 50±5% The workability of concrete mixtures was measured by flow table test. The slump values reported in this paper are the average of three readings obtained from three different mixes of each concrete.

2.2 Test methods

2.2.1 Compressive and tensile strength test

The compressive strength test was conducted on 150 mm cube specimens after 7, 28 and 90 days from casting. These measurements were carried out in accordance with PN-EN 12390-3. The tensile splitting strength test was conducted on the same type of specimens after 28 days from casting in accordance with PN-EN 12390-6. The compressive strength tests were carried out by using a ToniTechnic ToniPACT II instrument, having 3000 kN pressing capacity. The rate of loading was maintained at 0.5 MPa/s for compressive strength test and 0.05 MPa/s for tensile splitting test respectively. All mechanical properties of concrete were tested on six specimens from each series.

Tab. 1. Chemical and physical properties of cement, fly ash and silica fume.

Contents	CEM I 32.5 PC	fly ash Class-C FA	metakaolin MK	silica fume SF
SiO_2	21.7	60.5	42.0	92.0
Al_2O_3	5.0	5.45	52.0	0.70
Fe_2O_3	2.8	3.43	1.3	1.20
CaO	62.2	20.6	0.3	0.30
MgO	1.30	3.27	0.4	0.20
Na_2O	0.13	0.17	0.8	1.50
SO_3	2.80	4.42	-	0.30
K_2O	0.85	0.33	0.8	1.80
TiO_2	-	0.91	-	-
Loss of ignition [%]	3.22	0.74	1.5	2.00
Specyfic gravity [g/cm^3]	3.08	2.17	2.61	2.20
Bulk density [g/cm^3]	1.24	1.26	0.6	0.65
Fineness (>45 μm)	4.2	44.6	1.4	1.60
Specyfic surface [cm^2/g]	328	285	12000	22400

Tab. 2. Mix proportions (kg/m^3).

	I	II	III	IV	I R	II R	III R	IV R
cement	400	300	300	300	400	300	300	300
FA	0	200	200	200	0	200	200	200
sand	301	280	272	272	584	543	527	529
gravel	1468	1367	1327	1330	0	0	0	0
RCA	0	0	0	0	1073	999	970	973
SF	0	0	40	0	0	0	40	0
MK	0	0	0	40	0	0	0	40
HRWR	4	4	4	4	4	4	4	4
water	200	200	200	200	200	200	200	200
w/c	0.5	0.7	0.7	0.7	0.5	0.7	0.7	0.7
w/b	0.5	0.4	0.4	0.4	0.5	0.4	0.4	0.4

2.2.2 Sorptivity

The test was conducted by following the method described in [35] on the halves of the 150 mm cubes. The specimens had been prepared and cured as per PN-EN 12390-2. Prior to the research, they had been oven-dried to the permanent mass at the temperature of about 105°C. This guarantees that the so called "moisture history", described by Castro in [36], does not affect results of sorptivity measurement. The obtained value can be regarded as a concrete property and therefore can be used in direct comparison of different concretes. Drying in 105°C has some known disadvantages [36], but this is the only method that ensures the same level of specimens' moisture. The research was conducted at the temperature of 20°C. The specimens were weighed and then arranged in the vessel being dipped up to the depth of 5 mm. In specific time intervals from the moment of initiating research, the specimens were repeatedly weighed to define their mass gain resulting from water sorption. Subsequent mass measurements were conducted a total of 7 hours. Sorptivity S in g/(cm^2·h$^{0.5}$) was defined as a slope of the straight line expressing the dependence of the mass of the absorbed water (delta m) by the area (F) against the square root of time (t0.5) [35]:

$$\frac{\Delta m}{F} = S * t^{0.5} \tag{1}$$

2.2.3 Water penetration test

Depth of penetration of water under pressure was tested on 150 mm cubes after 90 days of curing. Specimens were water cured for 28 days and then stored in laboratory conditions (temperature 20±2C and RH = 50±5%). Water was applied on one of the smooth surfaces of the specimen under a pressure of 0.5 MPa. This pressure was maintained to be constant for 72 h. The water ingress was measured as the maximum penetration of the water front in three specimens.

2.2.4 Chloride migration coefficient test

The chloride penetration test was based on the standard of Nordtest Build 492 - Non-Steady State Migration Test. The principle of the test is to subject the concrete to external electrical potential applied across a specimen and to force chloride ions to migrate thorough it. After the specified period of time, depending of the initial current intensity, the specimen is split and sprayed with silver nitrate solution, which reacts with chloride ions to give white insoluble silver chloride precipitate. This enables a measurement of the depth to which the sample has been penetrated. The conformity criteria for concretes according to Non-Steady State Migration Test is based on the voltage magnitude, temperature of anolite measured on the beginning and end of the test and the depth of chloride ions penetration. The non-steady-state migration coefficient, D_{nssm}, is calculated by using the formula derived from the second Fick's law:

$$D_{nssm} = \frac{RT}{zFE} * \frac{x_d - \alpha\sqrt{x_d}}{t} \qquad (2)$$

where:
D_{nssm}: non-steady-state migration coefficient, [m^2/s];
U: absolute value of the applied voltage, [V];
T: average value of the initial and final temperatures in the anolyte solution, [K];
x_d: average value of the penetration depth, [m];
t: test duration, [seconds];

3 Results and discussion

Research results are presented in the Table 3. The given flow values of fresh concrete are the averages of three measurements, while the rest of the data are the mean values of six results.

3.1 Workability of concrete mixtures

It has been observed that the flow values of the concrete mixtures I - IV with natural coarse aggregate are tendenciously higher than of I R - IV R with RCA. Similar effect was observed in [37]. Series without the addition of fly ash (I and I R) showed significant segregation of components and low workability. Series II and III R showed tendency to segregate and had problems with workability. Addition of SF and MK in III, IV and III R, IV R mixes increased their flow values. All mixes with SF and MK addition showed no problems during casting.

3.2 Compressive strength of concrete

The compressive strength tested after 7 days was higher for concretes with RCA aggregates. The differences were 5.6%, 2.7%, 3.0%, 8.2% for I, II, III and IV series respectively. The highest strength (41.6 MPa) was reached for series IV R with MK additive. The lowest (29.1 MPa) for series II with fly ash and without other additives. Compressive strength after 28 days for the first three series (I-III and I R–III R) is higher for concretes with natural aggregate. The differences are 3.89%, 3.52% and 9.13% for series I, II and III respectively. Similar results were presented in [?C]. For series IV with the addition of MK higher strength was achieved for recycled aggregate concrete. The difference was 6.71%. The highest strength (52.5 MPa) was achieved for the IV R series made with fly ash and MK. The lowest strength was measured (39.1 MPa) on series II with fly ash and no other additives. Insignificant influence of RCA and fly ash on concrete strength after 28 and 90 days was also reported in [38, 39]. Compressive strength after 90 days for the first three series (I-III and I R – III R) is also higher for concretes mixed natural aggregate. The differences are 11.44%, 5.16%, 7.44% for series I, II i III respectively. For the IV series, with the addition of MK, higher strength was achieved on concrete with RCA. The difference was 7.66%. The highest strength (61.5 MPa) was achieved on the IV R series with fly ash and MK. The lowest (47.7 MPa) for the II series with fly ash and no other additives was measured. Similar results were presented in [37].

For each series the standard deviation of the results was low and the assignment of the corresponding compressive strength class of concretes was based on condition f_{cm}- 4 MPa. Table **??** summarizes the obtained concrete compressive strength classes after 28 days. Characteristic values of the compressive strength were also presented (f_{cm}- 4 MPa) after 7 and 90 days and. We have assessed their corresponding compressive strength classes as if they would have been at the age of 28 days. Theassesment was carried out in all cases in the same way (according to conformity Criterion 1 described in Table 14 in [40]). For each series an improvement in strength classes between 7 and 28 days of curing was observed as well as between 28 and 90 days. Strength class symbols are in bold in cases where there was an improvement of two classes. The lowest strength classes of all ages were reached by the II R series: C20/25, C25/30, C30/37 after 7, 28 and 90 days of curing respectively. The highest classes of all ages were reached by the IV R series: C30/37, C35/45, C45/55 after 7, 28 and 90 days of curing respectively.

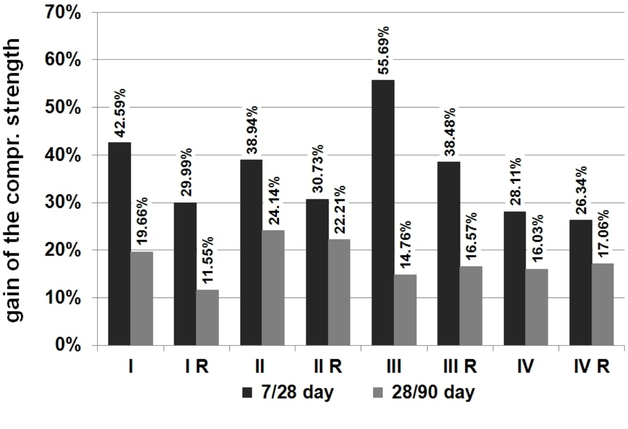

Fig. 1. Compressive strength gain in time.

Significantly higher strength gains occurred between 7 and 28 days of curing and higher increases were experienced for concretes which were mixed with natural aggregate. The difference compared with the increments of compressive strength of concrete with RCA for a series of I - IV and I R – IV R were 42.03%, 26.73%, 44.70%, 6.70% respectively. The compressive strength increases of concretes between 28 and 90 days

Tab. 3. Test results.

Mix	Flow	Compr. strength 7 d	Compr. strength 28 d	Compr. strength 90 d	Split. tensile strength	Water absorption	Sorptivity	Chloride migration coefficient	Water penetration
	[mm]	[MPa]	[MPa]	[MPa]	[MPa]	[%]	[cm/h$^{0.5}$]	[$\cdot 10^{-12}$m^2/s]	[mm]
I	520	32.3	46.1	55.2	2.98	5.70	0.152	11.33	37.3
I R	490	34.2	44.4	49.5	2.97	8.35	0.168	20.91	83.0
II	545	29.1	40.4	50.2	2.53	6.46	0.118	12.02	30.0
II R	500	29.9	39.1	47.7	2.61	8.72	0.162	19.52	101.0
III	660	30.7	47.7	54.8	3.36	7.23	0.126	6.10	14.3
III R	540	31.6	43.7	51.0	3.29	9.25	0.157	6.04	91.0
IV	770	38.4	49.2	57.1	3.51	7.47	0.130	4.19	20.6
IV R	690	41.6	52.5	61.5	3.81	9.04	0.155	3.79	32.6

Tab. 4. Obtained compressive classes of concretes.

	f_{cm}-4 MPa	corr. comp. str.	f_{cm}-4 MPa	str. class	f_{cm}-4 MPa	corr. comp. str.
MIX	7 days	class 7 days	28 days	28 days	90 days	class 90 days
I	28.3	C20/25	42.1	**C30/37**	51.2	**C40/50**
I R	30.2	C25/30	40.4	C30/37	45.5	C35/45
II	25.1	C20/25	36.4	C25/30	46.2	**C35/45**
II R	25.9	C20/25	35.1	C25/30	43.7	C30/37
III	26.7	C20/25	43.7	**C30/37**	50.8	**C40/50**
III R	27.6	C20/25	39.7	**C30/37**	47.0	C35/45
IV	34.4	C25/30	45.2	**C35/45**	53.1	C40/50
IV R	37.6	C30/37	48.5	C35/45	57.5	**C45/55**

for series I, I R and II, II R were higher than for concretes with natural aggregate, while for the series of concretes with the addition of microsilica and metakaolin (III, III R and IV, IV R) a greater increase in the compressive strength occurred than for concrete with RCA. The differences for series I - IV and I R - IV R were to 70.21%, 8.71%, 10.92%, -6.05% respectively. The highest increase in strength between 7 and 28 days occurred for series III, it was 55.69%. The smallest gain in strength during the same period, occurred for series IV R, it was 26.34%. Increases between 28 and 90 day were the highest for series II and III R with the addition of fly ash and without any other mineral additives. They were 24.14% for the concretes with natural aggregate and 22.21% for concretes with RCA. The smallest increase in strength occurred in this period for the series I R, it was 11.55%. There is not much difference between the tensile splitting strength between series with natural aggregate and RCA. The differences are 0.46%, -2.94%, 2.19%, 7.93% for series I, II, III and IV respectively. Not significant influence of RCA and fly ash on concrete splitting tensile strength is reported in [43]. The lowest strength occurred for series II and II R with fly ash and without any other additives. They were: 2.53 MPa and 2.61 MPa respectively. The maximum splitting tensile strength was reached by series IV with the addition of fly ash and metakaolin and with RCA aggregate. Analysis of the relationship between the mean values of concrete splitting tensile strength and concrete compressive strength after 28 days shows that the values f_{cm} / f_{ctm} vary from 6.25% (series II) to 7.51% (series III R). The mean value for all series is 6.87%, which is a typical value for concrete classes C25/30 to C35/45. Similar values of the strength ratio for concrete with RCA and fly ash is reported in articles [37, 39, 41, 42].

3.3 Sorptivity of concrete

The lowest sorptivity 0.118 g/(cm^2·h$^{0.5}$) was measured for concrete series II and the highest 0.168 g/(cm^2·h$^{0.5}$) for the I R. The addition of microsilica and metakaolin in the series III, III R, IV and IV R caused slight increase of sorptivity in comparison with the series II and II R in case of concretes with natural aggregate. For the concretes mixed with RCA the additions caused slight decrease. For the series with RCA sorptivity is generally higher than for series with natural aggregate. Differences are respectively: 10.69%, 36.89%, 24.78% and 19.41% for series I, II, III and IV. Negative impact of RCA was observed and reported in [37]. In [45] even bigger increase of sorptivity of RCA concretes was observed.

3.4 Depth of penetration of water under pressure

The highest penetration of 101 mm was recorded in the case of series II R while the lowest was obtained for concrete series III. Analysis of the results lead to the conclusion that use of RCA increases the depth of penetration of water under pressure for the same concrete mix proportions. The depth increased from twofold to over sixfold. Only in the case of series IV and IV R is the difference lower but still high 58.1%. Differences in the composition of concrete mixtures can not be translated clearly into trends of changes in the values of the water penetration depth. It can be stated only as a suggestion that the addition of metakaolin reduced the increase of the water penetration depth caused by RCA utilization but the increase remained significant.

3.5 Chloride migration coefficient of concrete

The highest value of the coefficient of chloride migration $20.91{\cdot}10^{-12}$ m^2/s was observed in the case of series I R. The lowest value equal to $3.79{\cdot}10^{-12}$ m^2/s was obtained for series IV R. In the case of series I, I R, II and II R clearly can be seen the influence of the used aggregate. RCA in the concrete instead of the natural aggregate significantly raised the migration coefficient. The differences are as follows: 84.5% when series I and I R are compared and 62.4% in case of series II and II R. Such an effect is not observed in the case of concretes made with the addition of microsilica and metakaolin, i.e. series III, III R, IV and IV R. In [38, 44] similar decrease of chloride migration coefficient for natural aggregate concrete after Class-C fly ash addition was reported.

For the latter two series the difference in values of chloride migration coefficient between the concrete made with RCA (series IV R) and the concrete with natural aggregate (IV series) was less than 9.54%. Analysis of the results indicates that the addition of microsilica and metakaolin offset the negative impact of the use of RCA on chloride migration coefficient. In [46] much more decrease of chloride migration coefficient for concrete with Class-F fly ash addition was reported. And the paper [39] reported negative influence of RCA on the chloride ion penetration and positive influence of SF addition for concretes with both RCA and natural aggregates.

Tab. 5. Estimation of the resistance to chloride ions penetration.

Diffusion coefficient	Resistance to chloride penetration
<2 x 10^{-12} m^2/s	Very good
2-8 x 10^{-12} m^2/s	Good
8-16 x 10^{-12} m^2/s	Acceptable
>16 x 10^{-12} m^2/s	Unacceptable

Comparing the obtained chloride migration coefficient values with Table 5 [47, 48] shows that value for I concrete $11.33{\cdot}10^{-12}$ m^2/s and $12.02{\cdot}10^{-12}$ m^2/s for II concrete are in the ”Acceptable” range. RCA increased chloride migration coefficient values for I R and II R concretes to the ”Unacceptable” level. On the contrary metakaolin, silica fume with fly ash addition lowered chloride migration coefficient to the ”Good” value.

4 Conclusions

The study was primarily conducted to test the possibility of using aggregate obtained from crushed old concrete pavements in concrete manufacturing with addition of SCM.

Replacement of natural coarse aggregate 2-16 mm with RCA made of the low-quality old concrete pavement plates allows to obtain concrete with similar strength parameters. Replacing part of the cement with C-class fly ash only slightly reduces the compressive and tensile strength of concrete. The effect of the RCA in the decrease in durability prognostics of the concrete structure should be also noted. This is particularly visible in the case of water permeability, water absorption and rate of chlorides migration. The negative impact of the RCA can be reduced by the addition of microsilica or metakaolin as a microfiller. Influence of recycled aggregates on the durability of concrete structures should be the subject of further research. Research presented in the paper allowed to draw the following conclusions:

- Usage of RCA as a substitute for natural aggregates allows to obtain similar classes of concrete strength but it affects negatively some of its parameters associated with the durability.
- Water absorption of RCA concrete is higher by several tens of percent then water absorption of concrete with natural aggregate.
- Sorptivity of concrete with RCA is more than ten percentages greater than the sorptivity of concrete with natural aggregate.
- Chloride migration coefficient of concrete with RCA without the addition of microsilica or metakaolin is almost twice higher than in the concrete with natural aggregate.
- Depth of penetration of water under pressure of concrete with RCA is up to six times greater than of concrete with natural aggregate. The addition of microsilica and metakaolin reduces the difference but there is still tens of percentages as detriment.
- It is possible to make concrete of good technological parameters and strength by using of RCA, however, this kind of aggregate should be used carefully due to the potential negative impact on the durability of the structure.

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